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INTERACTION OF FIRE AND SIMULATED BLAST DEBRIS

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ABSTRACT

A reusable full-scale fire test facility, designed, constructed and instrumented by IIT Research Institute for the Office of Civil Defense, has been operated to gather information on the flow of heat and fire gases into unsealed basement shelters. The full-scale structure has many of the controlled features of a laboratory experiment and adapts to systematic study of parameter variation. It can also serve to spot check results of analytical or small-scale laboratory studies. Activities included fire experiments with varied amounts and types of combustible and noncombustible loading over and beyond the shelter space. Also there were experiments in which water was added to the top of the shelter ceiling slab to moderate the peak heating period. Debris removal from the slab and from venting points has been examined. An analytical model of the heat flow through the shelter slab has been constructed to aid in the projection and evaluation of countermeasure effectiveness.

Results to date indicate that debris fires contained within the structural interior do not tend to direct toxic gases toward near-ground vent locations. However, wind induced pressures in

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the fire zone can drive concentrated fire gases through faults in the shelter ceiling, which may pose a problem should total button-up systems be considered. Heat fluxes, as expected, have been found to vary with fire load. A residential occupancy with light partitions produced heat transmission through a 12 in. shelter ceiling slab equivalent to that which would be produced by the occupants. For a thinner slab (5 in.), this increases to the equivalent of four added occupants per shelter space. A heavily loaded occupancy (library) produced a peak heat load equivalent to seven occupants per shelter space through a 5 in. ceiling slab or 2-1/2 occupants per space through a 12 in. slab. Water added to the top of the shelter ceiling slab at a density of 1/3 gal/ft^2 during a residential debris fire reduced the peak heating of the shelter interior to 25 percent of that observed without water addition. Debris removal from the ceiling slab after peak burning has also produced significant reduction in heat load on the shelter space.

Debris removal from the immediate vicinity of intake vents mitigates the severity of toxic gases. Deep debris with high noncombustible content produces longer lasting, lower intensity fires which may contribute to a degradation of general area-wide air quality.

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Final Report IITRI-J6217 (2)

Contract DAHC 20-70-C-0406
Work Unit 1135A

FIRE LABORATORY TESTS - PHASE II
INTERACTION OF FIRE AND SIMULATED BLAST DEBRIS

by

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February 1972

FOREWORD

This final technical report is a summary of studies on Contract DAHC 20-70-C-0406, OCD Work Unit 1135A (IITRI Project J6217), entitled "Fire Laboratory Tests - Phase II: Interaction of Fire and Simulated Blast Debris." This program is sponsored by the Office of Civil Defense, Office of the Secretary of the Army, Washington, D.C. 20310, with Mr. Norward A. Meador as Technical Monitor. The contract was initiated on 1 July 1970. Project activity from 1 July 1970 to 31 December 1971 is reported herein.

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FIRE LABORATORY TESTS - PHASE II
INTERACTION OF FIRE AND SIMULATED BLAST DEBRIS

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Results to date indicate that debris fires contained within the structural interior do not tend to direct toxic gases toward near-ground vent locations. However, wind induced pressures in the fire zone can drive concentrated fire gases through faults in the shelter ceiling, which may pose a problem should total button-up systems be considered. Heat fluxes, as expected, have been found to vary with fire load. A residential occupancy with light partitions produced heat transmission through a 12 in. shelter ceiling slab equivalent to that which would be produced by the occupants. For a thinner slab (5 in.), this increases to the equivalent of four added occupants per shelter space. A heavily loaded occupancy (library) produced a peak heat load equivalent to seven occupants per shelter space through a 5 in. ceiling slab or 2-1/2 occupants per space through a 12 in. slab. Water added to the top of the shelter ceiling slab at a density of 1/3 gal/ft^2 during a residential debris fire reduced the peak heating of the shelter interior to 25 percent of that observed without water addition. Debris removal from the ceiling slab after peak burning has also produced significant reduction in heat load on the shelter space.

Debris removal from the immediate vicinity of intake vents mitigates the severity of toxic gases. Deep debris with high noncombustible content produces longer lasting, lower intensity fires which may contribute to a degradation of general area-wide air quality.

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FIRE LABORATORY TESTS - PHASE II
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1. INTRODUCTION

Fire and its effects on shelter occupants, caused either by explosion of a nuclear weapon or by subsequent events, has been of concern to the Office of Civil Defense (OCD) for many years. The nature of the research efforts has varied in keeping with the continuing evolution of OCD shelter philosophy. The present study encompasses analytical and experimental investigations leading to the development of information to provide a sound technical base from which to design occupant fire protection into basement shelters in new construction. Specific goals are to:

(1) Evaluate the flow of smoke, toxic gases and heat into basement shelters from various types of fire load in the building above the shelter.

(2) Develop recommendations on permissible fire load in the building above a basement shelter.

(3) Develop recommendations on the location and capacity of ventilation intakes for basement shelters with the objective of obtaining the least expensive air intake consistent with 85 to 95 percent survival of shelterees.

(4) Develop recommendations for fire control methods to be used with blast slanted basement shelters and assuming considerable blast damage to the building above the shelter.

(5) Conduct and evaluate experiments to determine ventilation problems in basement shelter associated with fire loads on first and second floors and debris fires extending well beyond the bounds of the structure.

(6) On the basis of preliminary tests previously conducted, perform experiments to evaluate the effect of water countermeasures.

(7) Evaluate the effect of other expedient type countermeasures (e.g., removal or scattering of debris during and/or after start of fire).

(8) Evaluate effect of operating emergency ventilating equipment during fire period.

These goals reflect the concept of slanting new construction (i.e., incorporating modifications during the design stage) to provide shelters with enhanced resistance to the combined effects of nuclear weapons; blast, fire and fallout. There is little question that below grade shelters of concrete construction designed to withstand 10 psi or more overpressure, can also maintain structural integrity under all imaginable fire exposures. Questions to be answered are to provide life safety for the shelter occupants from penetration of heat and fire gases into the shelter space. These include both fire environments; as determined by fire load and level of blast damage, and as modified by various conceptual countermeasure activities.

The studies reported herein center around large-scale fire experiments. These are being conducted in a reusable two-story fire test facility which provides a 60-man (600 ft^2) basement shelter, fully instrumented for assessment of the flow of heat and fire gases. By providing for full-scale experiments under laboratory conditions, the facility is adaptable to a systematic study of effects of variable parameters, as well as to spot check applicability of designs based on theoretical or small-scale laboratory studies.

Included in the first year of effort were construction and general instrumentation of the large-scale fire test facility as well as conduct of preliminary tests. Reference 1 provides a detailed report of this portion of the program. During the current reporting period (July 1970 to Dec 1971) further instrumentation has been added and experiments have been conducted for debris piles within and beyond the bounds of the structure above the shelter. These have been augmented by development of an analytical model of heat flow through the shelter ceiling slab and by conducting several small-scale debris tests on an aluminum plate. Their purpose is to aid in assessing the potential benefit of debris removal and water application as countermeasure techniques and to aid in predicting the heating effects as other debris piles or thicknesses of ceiling slab are considered. Several large-scale countermeasure benefits have also been examined.

2. THE FIRE TEST FACILITY

The large-scale fire experiments are being conducted in the test facility constructed under Contract DAHC 20-70-C-0206 (Ref. 1). This facility consists of a 20 by 30 ft basement shelter space topped by a two-story reinforced concrete rigid frame upper shell. The shelter ceiling is a 12-in.-thick reinforced concrete slab. Two outside shelter entrances, a ramp and a stairwell provide locations for assessing entryway debris pileup as well as for evaluating ventilation intakes. Photographs of the structure are shown as Fig. 1, and a plan view is included as Fig 2. As presently constructed, the facility has the fire zones approximately 50 percent enclosed. This can be readily increased by the addition of temporary panels to the remaining openings. As shown by Fig. 2, portions of the shelter ceiling (first story floor) and the second story floor can be removed to vary the fire zone configuration and its access to the shelter space. In addition, changes in shelter ceiling thickness or composition can be studied at these locations. For further construction detail, the reader is referred to Ref.1.

All features of the instrumentation reported in Ref. 1 have been retained. These include numerous temperature measurements in the fire areas, on and within the shelter ceiling slab and within the shelter space. Heat flows are measured through the main ceiling slab and the inserts. Concentrations of CO, CO_2 and O_2 are measured in the shelter, its entryways and over the surrounding ground areas. Humidity and smoke are also measured in the shelter space. Pressure differences between the shelter, the upper structure and a remote ambient are monitored. General weather data are collected along with an official description provided by the weather bureau.

During this reporting period, thermocouples have been added within the shelter ceiling slab to aid in definition of vertical gradients through the slab and thus determine the way in which moisture migration is affecting heat loading.

Ramp Entrance

Overall View of Structure

Stairwell Entrance
(Behind Right Rear Wall
in Overall View)

Fig. 1 FIRE TEST STRUCTURE AND SHELTER ENTRANCES

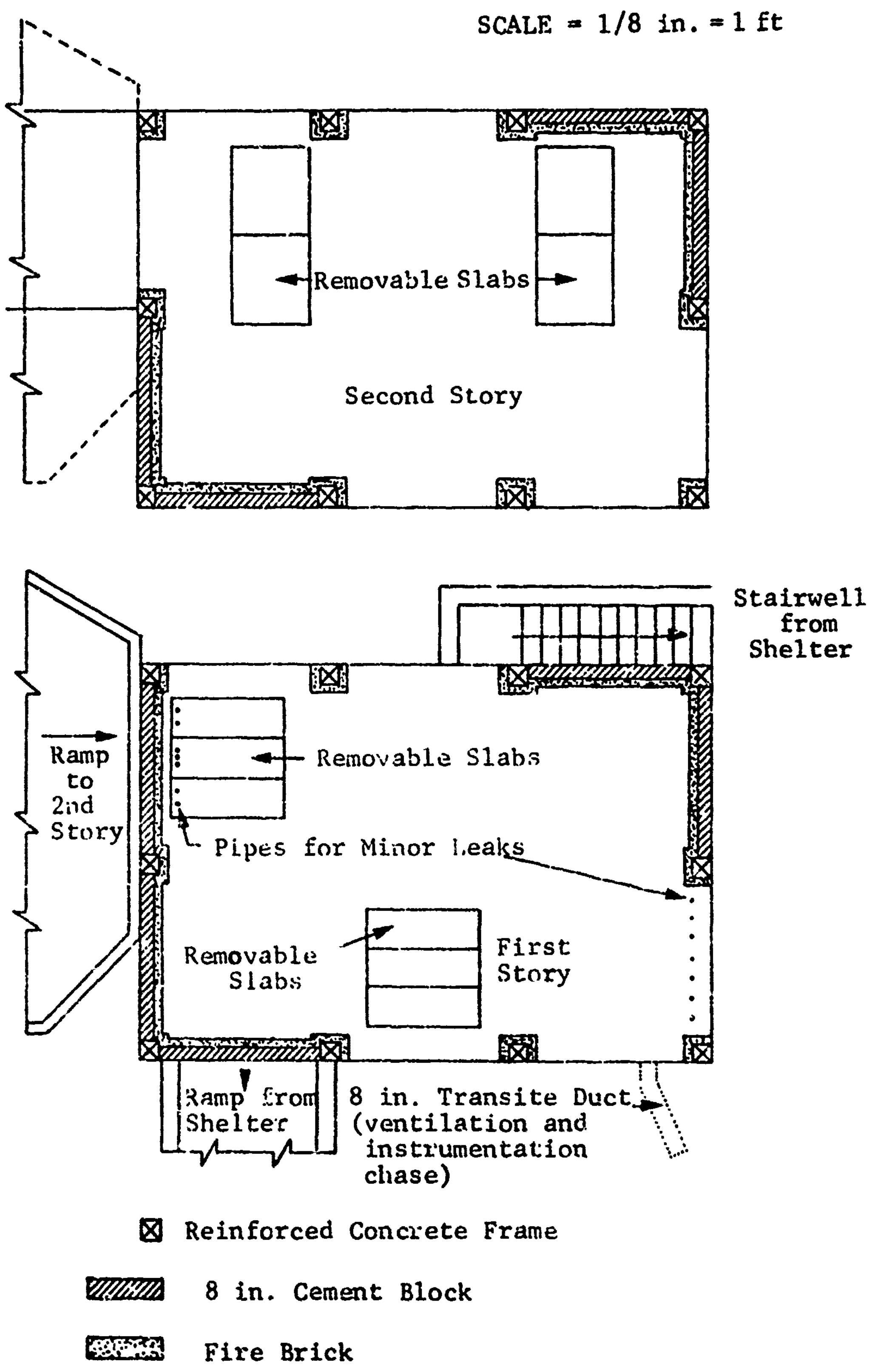


Fig. 2 PLAN VIEWS OF FIRE TEST FACILITY SHOWING GENERAL CONSTRUCTION FEATURES

Pans have been attached to the lower ceiling surface which separate and collect moisture that has moved through the slab during the experiment either as liquid or as vapor. One set of pans is shown schematically in Fig. 3. The uppermost pan collects liquid water dripping from the shelter ceiling. It is insulated on its lower surface so that it remains at temperatures like those of the ceiling slab. Vapors pass through the protected holes in this pan and condense on the lower pan. Surfaces of the lower pan are maintained at temperatures like those of the shelter floor by circulating water from a reservoir through coils on the pan.

Added thermocouples have also been placed on both faces of the shelter ceiling slab. These aid in judging average conditions, a task that is complicated by the nonhomogeneous nature of the debris. The number of gas sampling locations on the grounds surrounding the structure has been increased to encompass a larger total area. In addition, gas sampling and temperature measuring points have been added to the ramp entry to further identify conditions of debris burning in that area.

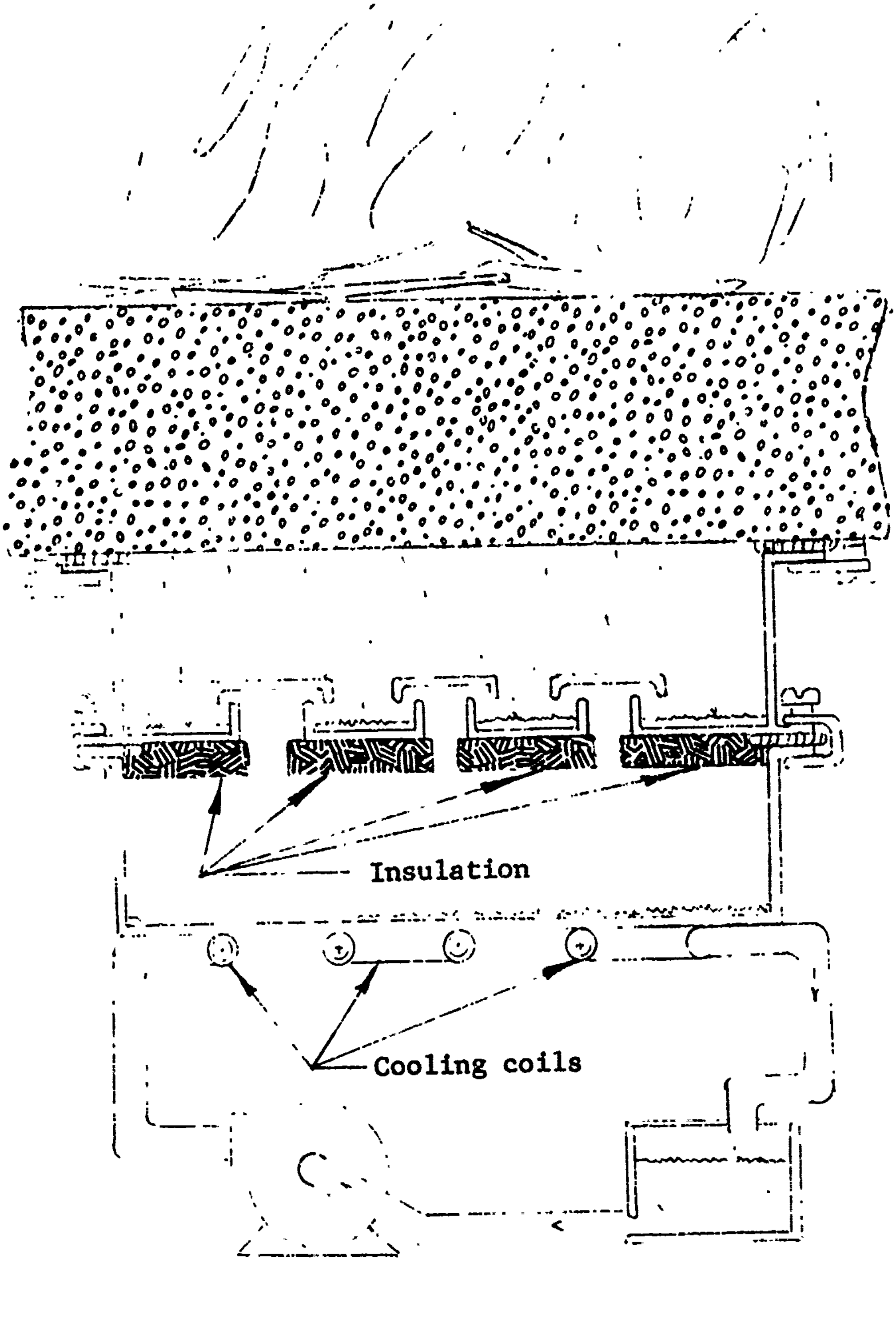


Fig. 3 SCHEMATIC OF MOISTURE COLLECTING/SORTING SYSTEM (not to scale)

3. SCHEDULE OF EXPERIMENTS

Numerous parameters require evaluation in this continuing program to properly assess fire vulnerability of occupants in the basement of a blast and/or fire slanted shelter. To serve this purpose, a series of experiments has been scheduled, subject to review in the light of each set of results obtained. It includes those experiments conducted during the previous study and extends well beyond the scope of the present level of effort. The experiments are designed to search out problem areas and/or to examine conceptual solutions. Thus, they are not, taken as a group intended to represent the average situation to be expected in blast-fire-fallout environments. They may represent only a portion of some fire environments, but one which can be combined with other portions to evaluate a total effect. For example, the time history of heat flows through the shelter ceiling for appropriate fire loads within the structure can be added to descriptions of the gases produced by debris extending over the general ground area to provide approximate descriptions of those situations where a combination of the two exists. In examining the data, one can also consider the test structure to be a total shelter or to represent one portion of a larger structure.

The particular ventilation scheme examined by a specific experiment is usually not the optimum for the fire situation created, but is designed to identify problem areas and constraints on ventilation use. The schedule of experiments now stands as described in the following subsections.

3.1 Well Ventilated, Contained Debris Fires

This series of experiments assumes that blast has removed glazing and, in most cases, has destroyed interior partitions. However, exterior walls are assumed to survive and the debris is confined to the general bounds of the building. Surrounding structures are assumed to be sufficiently strong or far enough

away not to add significant debris near the building exterior. Six experiments have been conducted to date and are reviewed here.

1. Retail Furniture Store Occupancy: light interior partitions, blast assumed to destroy interior partitions, (Experiment 70-1, May 1970).

This occupancy contains combustible items common to a residence but in higher concentration (7-1/2 lb ft^2 floor area compared to 3-1/2 lb ft^2 for a residence). Noncombustible contents are much higher than those of a residence (4-1/2 lb ft^2 compared to 1-1.2 lb ft^2) due mostly to display racks, counters, etc. For the experiment, real contents items were placed in the structure (limited to the first story unless otherwise noted), appropriately overturned or scattered and mixed with added lumber, wallboard (rock lath was used) and ceiling tile which represented the structural debris from ceiling cover and interior partitioning.

2. Residential Occupancy: light interior partitions, blast assumed to destroy interior partitions (Experiment 70-2, June 1970).

This occupancy represents that which can be expected as most common to potential slanted new constructions. For this experiment, the contents were distributed with structural debris in the same manner as described for 70-1. As in 70-1, the exterior walls were 50 percent open.

3. Residential Occupancy: light interior partitions, blast assumed to remove glazing but not interior partitions (Experiment 70-3, August 1970).

By assuming a lower blast level, the light structural noncombustibles were retained in place until the latter stages of the fire. This sequence of events produced a less serious heat load on the shelter ceiling as the contents burned quickly and delivered most of their heat into the air. The exterior walls were 50 percent open.

Under more restricted ventilation of the structure (less windows) the reduction in heat load on the shelter can be expected to be less pronounced.

4. Office Occupancy: light interior partitions, blast assumed to destroy interior partitions (Experiment 70-4, September 1970).

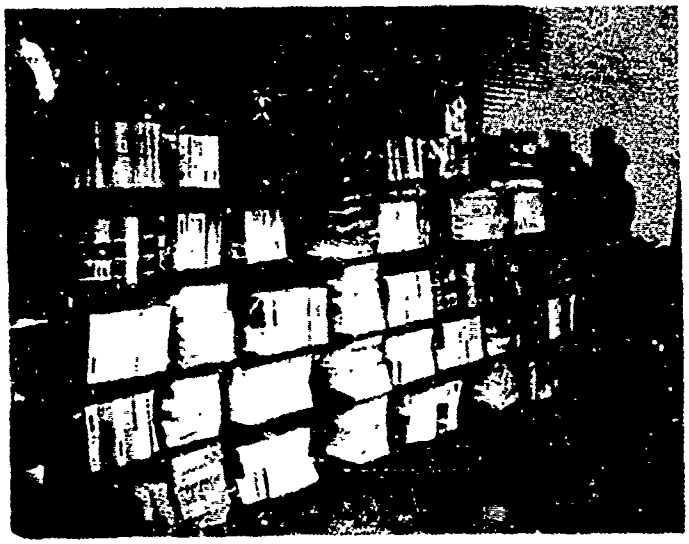
This occupancy contains fuel weights similar to those of a retail furniture store (70-1) but the fuel is more densely packed (more books and wood and less clothing and upholstered furniture). The produced fire burned more slowly and was more efficient in heating the shelter. Part of this increased efficiency was due to the retention of a fairly continuous blanket of ash which reduced the ability of the slab to lose heat upward after the main fire was over. Removal of the ash could be an effective countermeasure.

5. Residential Occupancy: masonry interior partitions, blast assumed to destroy interior partitions (Experiment 70-5, October 1970).

This debris had a greatly increased noncombustible weight over that used in experiment 70-2 (residential with light interior partitions). Although it had been suspected that the added noncombustibles might effectively store heat for later delivery through the shelter ceiling slab, this was not the case. The stored heat was apparently readily released to the atmosphere with the net effect being a lower rate of heat input to the shelter during the peak heating period.

6. Library Occupancy: masonry interior partitions, blast assumed to destroy interior partitions (Experiment 70-6, November 1970).

This fire involved a very high fuel load (see Fig. 4) and can serve as an upper bound against which to interpolate the results of occupancies of intermediate loading. Active flaming was moderate (also see Fig. 4) but longer lasting than that of previous fires. The shelter heating peaked slowly at a level lower than might be expected but remained high for a period of days.



Contents Load Being Installed Prior to Dumping
and Mixing with Structural Debris
(Note: String Ties Cut Prior to Dumping)

Active Burning Period

Fig. 4 SHELTER BURN 70-6: LIBRARY OCCUPANCY

Table I provides a summary of configurations used for the well ventilated, contained debris fires.

3.2 Water Countermeasure

These experiments introduce water on the upper surface of the shelter ceiling (first story floor). The water is not directed toward extinguishing the burning debris but is added in a layer to cool the slab surface. In particular, it is designed to reduce the heating rate of the shelter during the peak period. No attempt to flood the space is being made; rather, water is added at a rate to produce a very light cover which may not be quite complete. This approach offers simplicity of operation so that it may be applied as shelter protection in the field.

The first of these experiments was conducted for a residential loading with water application delayed about 2 hours after ignition, well beyond the peak fire. Water effectiveness was low with this great a delay in application in that the surface cooled well below boiling with the first portion of water added and the bulk of the heat had penetrated beyond easy recovery even though it had yet to reach the shelter interior. A second experiment was then constructed for which application of water was initiated earlier. The results of this experiment indicated that the shelter peak heating rate was reduced to 25 percent of that observed without water addition. Added experiments were conducted with an artificially uniform (homogeneous) load and are being used to aid in validation of the descriptions of heat flow in the computer model as well as in further predictions of water countermeasure effectiveness.

3.3 Study of Shelter Vents

For these experiments, debris is extended well beyond the bounds of the structure and totally encompasses at least one shelter entrance. This entrance is used as a ventilation point. Comparisons are being made between local gas concentrations and

Table I

SUMMARY OF SHELTER EXPERIMENT CONFIGURATIONS
FOR WELL VENTILATED, CONTAINED DEBRIS FIRES

Burn Number	70-1	70-2	70-3	70-4	70-5	70-6
Occupancy	Furniture Store	Residential	Residential	Office	Residential	Library
Interior Partitions	Light	Light	Light	Light	Heavy	Heavy
Damage* to Interior Partitions	Destroyed	Destroyed	Negligible	Destroyed	Destroyed	Destroyed
Contents Fuel Load lb/ft^2	7.5	3.5	3.5	7.5	3.5	24.0
Contents Non-Combustibles lb/ft^2	4.5	1.5	1.5	4.5	1.5	2.0
Structure Fuel Load lb/ft^2	0.6	0.6	0.6	0.6	1.5	1.5
Structure Non-Combustibles lb/ft^2	3.0	3.0	3.0	3.0	45.5	45.5
Structural Non-Combustibles ft^3/ft^2 Floor Area	0.076	0.076	0.076	0.076	0.35	0.35
Contents Fuel Surface/ Floor Area	4	3	3	1-2	3	5

*All burns with 50 percent openings in exterior walls (assumed to be blast removed glazing).

temperatures above the debris and those encountered in the relatively high volume airflow being used by the shelter. The experiments consider several debris concentrations representative of those which might be distributed from the shelter building and/or from surrounding structures. One experiment is contemplated which retains a previous debris density and increases the ground area covered.

To date, one experiment has been conducted with moderately low debris density extended some 30 ft in all directions beyond the shelter ramp entrance. This has shown that a period exists during which air should not be drawn directly over the debris into the shelter. A second experiment arranged the same debris over a slightly larger area but with a 15 ft cleared radius extending outward from the air intake. A benefit was obtained of reduced CO and CO_2 concentrations and cooler entering air. Experiments have been constructed to simulate a deeper accumulation to provide preliminary assessment of the button-up time associated with attempts to pull air through the debris layer, and of the active fire duration which might be associated with deeper or more restrictively ventilated debris.

Experiments in this category will form a future effort. Debris depth, quality and distribution will be varied further. At least one fire of significantly larger ground coverage will be included. This fire will be designed from predicted debris distributions from real structural arrangements.

3.4 Debris Removal Countermeasure

These experiments may take the form of an evaluation of activities to remove fuels before they burn or of the uncovering of the shelter ceiling slab (or critical portions) to aid cooling after the peak fire. Actual operations are being considered and the experiments would include the necessary auxiliary conditions to develop behavioral constraints representative of a total attack environment. To date several experiments have been

conducted which show that an advantage is gained by clearing around a vent or uncovering the ceiling slab after the peak fire to promote upward cooling. These have not evaluated the reaction to or capability of the shelteree in performing the tasks. Such will be initiated in the future.

3.5 Shelteree Behavior

While much study has been performed on the behavior of shelterees under the restrictions of shelter confinement, little can be said with certainty as to their reaction to the added stresses produced by the indicators of a fire raging beyond the shelter envelope or their willingness to approach even to fringes of a fire area to perform countermeasure activities. Future activities will initiate studies to evaluate shelteree behavior under threat of external fire both when they remain within the shelter and when they attempt countermeasure activity as mentioned earlier. The first step will be to review shelteree behavior under nonfire conditions and to examine the physical manifestations of the external fire that appear within the shelter space under various modes of shelter operation. The limitations on experimentation imposed by fire sizes and configuration used at the laboratory facility will also be examined to determine what artificial constraints should be added for shelteree behavior studies. All will be incorporated into the design, conduct and evaluation of experiments deemed feasible.

3.6 Experiments at Reduced Ventilation

Future experiments in this category will be conducted with exterior wall openings of less than 25 percent. The effect of a greatly restricted air supply may well cause a fire that smoulders and produces much larger amounts of toxic gases directly over the shelter. This portion of the study should include consideration of realistic shafts and wells which extend into the basement (shelter) level. These are being considered in present efforts only to the degree that they might be compatible with the primary goals listed in the scope of work.

4. SELECTED EXPERIMENTAL RESULTS

Experiments conducted during 1970 are summarized in Table I. Table II briefly describes the experiments conducted during 1971.

Table II

SUMMARY OF EXPERIMENTS CONDUCTED IN 1971

Experiment	Debris Fire Load	Remarks
71-1	Residential, Light Partitions Destroyed	Water countermeasure applied 2 hours after ignition.
71-2	Residential, Light Partitions Destroyed	Water countermeasure applied at peak fire (approx. 3/4 hour after ignition).
71-3	Debris Crib*	Water countermeasure applied to selected portion of slab, debris allowed to remain.
71-4	Debris Crib	Water countermeasure applied to selected portion of slab, debris removed from entire slab after peak fire.
71-5	Extended Residential	Debris in and around shelter, shelter vented at 900 cfm.
71-6	Extended Residential	As above but debris cleared from vicinity of intake vent, shelter vented at 900 cfm.
71-7	Deep Residential Includes Total Structure	Debris depth increased to gain insight on its effects on time of burning, gases generated, significance of buried vents.
71-8	Deep Residential	Pile compacted, dirt intermixed to determine importance on burning behavior.
71-MP1, 2,3,etc.	Debris Crib	A series of auxiliary debris fire experiments placed on an aluminum plate to aid in assessing heat flows and water countermeasures effectiveness.

*The term "debris crib" is used to describe artificial debris piles created from wood cribs interlaced with drywall. This technique was used to provide a fuel load that is more uniform in horizontal directions.

4.1 Heat Flow through Shelter Ceiling Slab

Typical heat fluxes transmitted through the 12-in.-thick main shelter ceiling slab are shown in Fig. 5. For purposes of comparison, the results of previous experiments also are included.* Table I summarizes the experimental conditions for each burn. Figure 6 compares the rise in shelter air temperature 1 ft below the ceiling. Since no significant ventilation of the shelter space was undertaken, the shelter space can be considered to approximate a large calorimeter. Thus, the measured relative levels of shelter heating can be confirmed by examining the relative rise of the shelter air although some uncertainty is introduced if outside ambient temperatures are in a period of rapid change. Examination of Figs. 5 and 6 shows that the debris containing heavy partitions (burn 70-5) was not as effective at heating the shelter as was that with light partitions (burn 70-2). The penalty for placing shelter spaces under heavily loaded occupancies is clearly shown by burn 70-6 although the levels reached are not linearly related to fire load. The levels of heat transmission through the 5 in. slab sections reached 285 Btu/hr-ft^2 during burn 70-6 which represents an added load equivalent to seven occupants per shelter space. In addition to being higher, heat transmitted through the 5 in. slab sections reaches significant proportions much sooner. The time delay of heating afforded by the thicker (12 in.) slab offers a significant benefit in that many fires will be past their period of active gas generation before the heat load becomes severe so that the two problems are not simultaneous.

The experiments listed in Table I and shown in Figs. 5 and 6 were conducted with no ventilation of the shelter space. The possibility that ventilating the space might measurably increase the heat leaving the slab was of some concern. Steps were taken during experiments 71-5 and 71-6 to examine this possibility.

*Results of 70-1 are low due to the high moisture content of the shelter slab. This is discussed in the Phase I Report (Ref. 1).

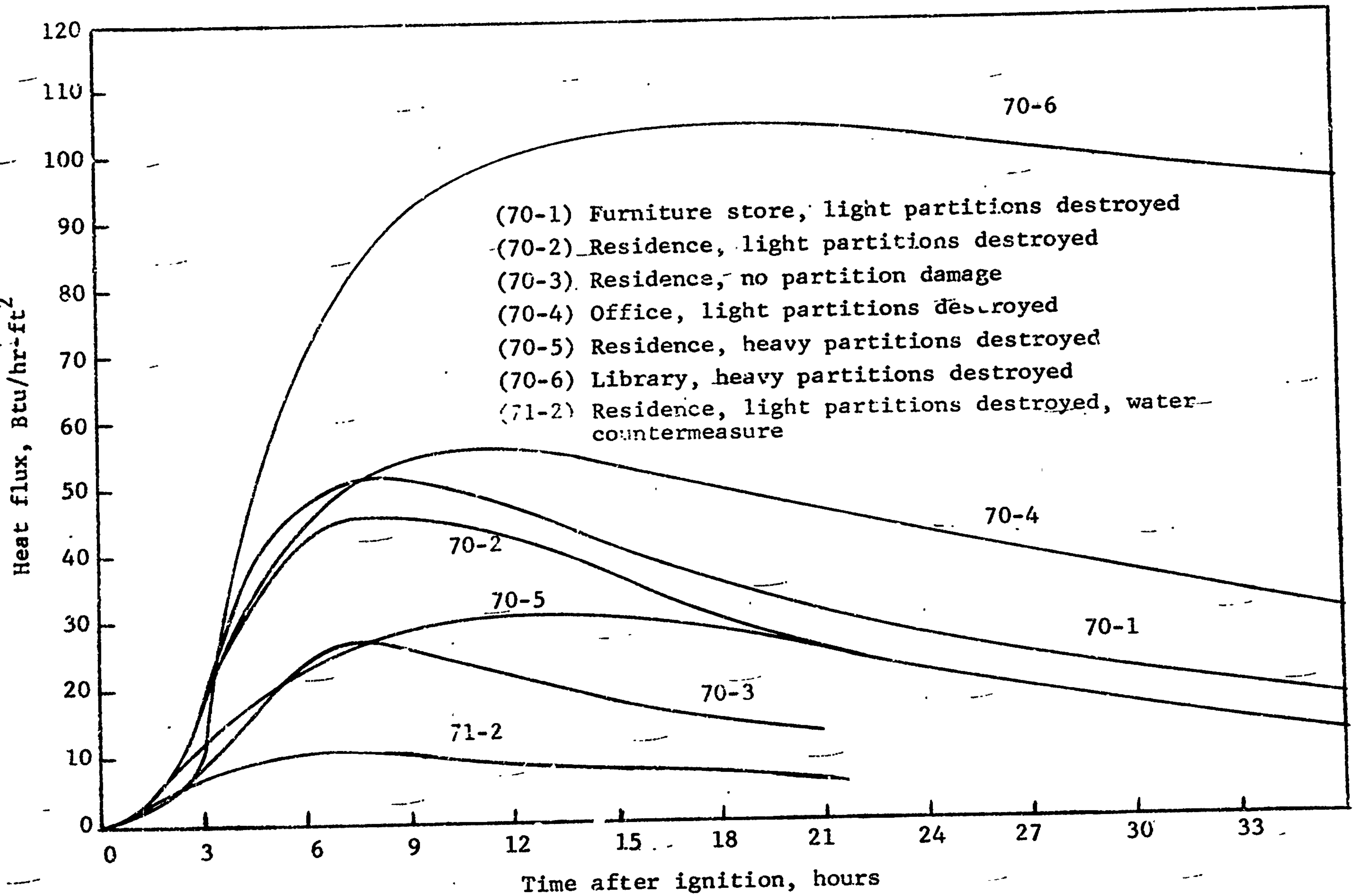


Fig. 5 HEAT FLUX THROUGH 12 in. SHELTER CEILING: AVERAGE OF SIX LOCATIONS

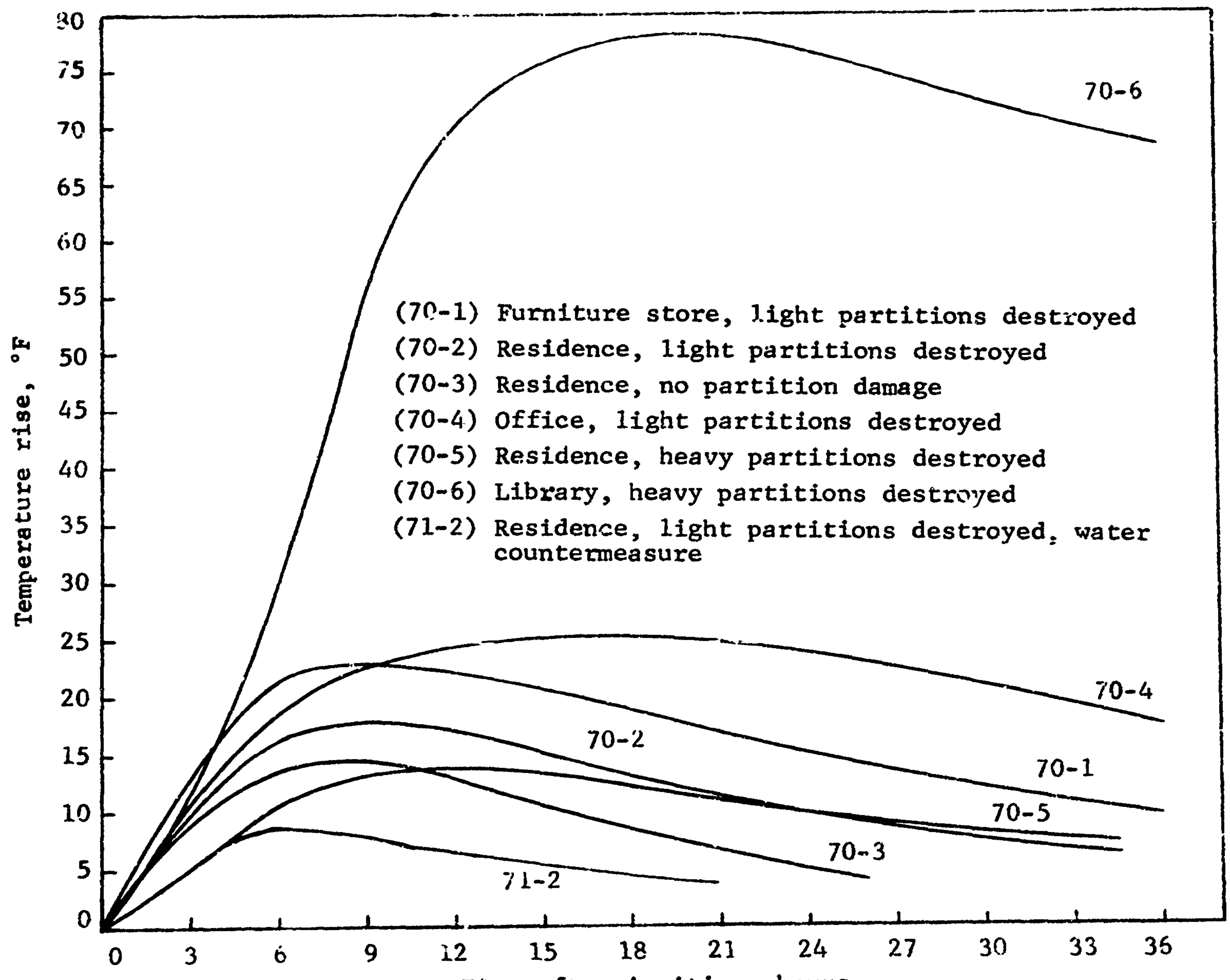


Fig. 6 AIR TEMPERATURE RISE IN SHELTER, 1 ft BELOW CEILING

These experiments had debris beyond the shelter building but also had a residential debris loading above the shelter. They were conducted with 900 cfm air drawn through the shelter (15 cfm/occupant space). Two circulating fans were placed at the floor in diagonally opposite corners to provide additional circulation within the shelter space. Examination of airflow at various locations near the ceiling slab indicated flows of the order of 1 ft/sec moving in random directions. This air motion was not sufficient to appreciably affect the net heat flow through the ceiling slab, and the measured heat flows in experiments 71-5 and 71-6 duplicate those of experiment 70-2 which had the same debris loading but no shelter ventilation.

4.2 Countermeasures Applied to Shelter Ceiling Slab

4.2.1 Water Countermeasure Applied to a Residential Debris Fire

Water was applied to the shelter ceiling for two residential debris fires as described in subsection 3.2. For the first of these experiments (71-1), the water was added about 2 hours after ignition and little benefit was gained. Figures 5 and 6 present results for experiment 71-2 in which water was introduced on the top of the shelter ceiling immediately after the peak fire was reached. The fire was in a debris pile representative of a residential occupancy with light interior partitioning destroyed by blast (same as 70-2). Water was applied to a density of 1/3 gal/ft^2 which would require a water supply equivalent to that stored for drinking purposes. A marked reduction in shelter heating was achieved, (about 75 percent) far better than what one would predict by assuming the water only removed heat from the concrete surface. This will be discussed in greater detail in a following section on computer modeling of heat flow in the shelter ceiling slab.

4.2.2 Water Countermeasure and Debris Removal Evaluation using Cribs

In order to provide a more uniform debris pile, a crib of wood sticks capped with sheets of plasterboard was devised and used to cover the entire shelter slab. The makeup of this debris crib was later used with smaller scale tests and is shown in Fig. C-2 of Appendix C.

Experiments 71-3 and 71-4 used this debris crib. In 71-3, one small area was treated with a water countermeasure. In 71-4, this area was again treated with water and then the entire debris pile was removed once the fire began to subside. The purpose of the debris removal was not just to remove the heat source but also to remove the insulation caused by ashes and noncombustibles so that the slab could cool to the upper air.

The effectiveness of the countermeasures can be judged by examination of Fig. 7 which shows peak shelter heating due to this fire was reduced from 57 Btu/hr-ft^2 to 44 Btu/hr-ft^2 by the addition of 1/3 gal/ft^2 water to the upper slab surface*; to 37 Btu/hr-ft^2 by removing the debris 1-1/2 hr after ignition; and, to 13 Btu/hr-ft^2 by the combined countermeasures. Although the exact magnitude of each curve is subject to some error due to the limited (1 to 3) heat flow meters monitoring each area and some interaction of areas, the benefit is clearly demonstrated. Early portions of the curves are not shown as steam leaving the 5 in. slab sections flowed along the shelter ceiling causing random gyrations in the data records.

A second representation of the benefit gained by the debris removal is shown in Fig. 8 which compares air temperatures 1 ft below the ceiling of the unvented shelter (this type of comparison was used in earlier reports to verify results produced by heat flow meters). It should be remembered that the results are slightly perturbed by the fact that the shelter ceiling does have several thin sections and that 36 ft^2 was treated by water in each experiment. However, the maximum temperature rise of 40°F caused by the debris crib (a very severe exposure in spite of its low fuel content) was reduced to 20°F by debris removal 1-1/2 hours after ignition.

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* The water countermeasure appears less effective against the crib fires than against real building and contents debris. The reason for this is not clear at this time but is probably related to debris geometry and/or relative time of water application.

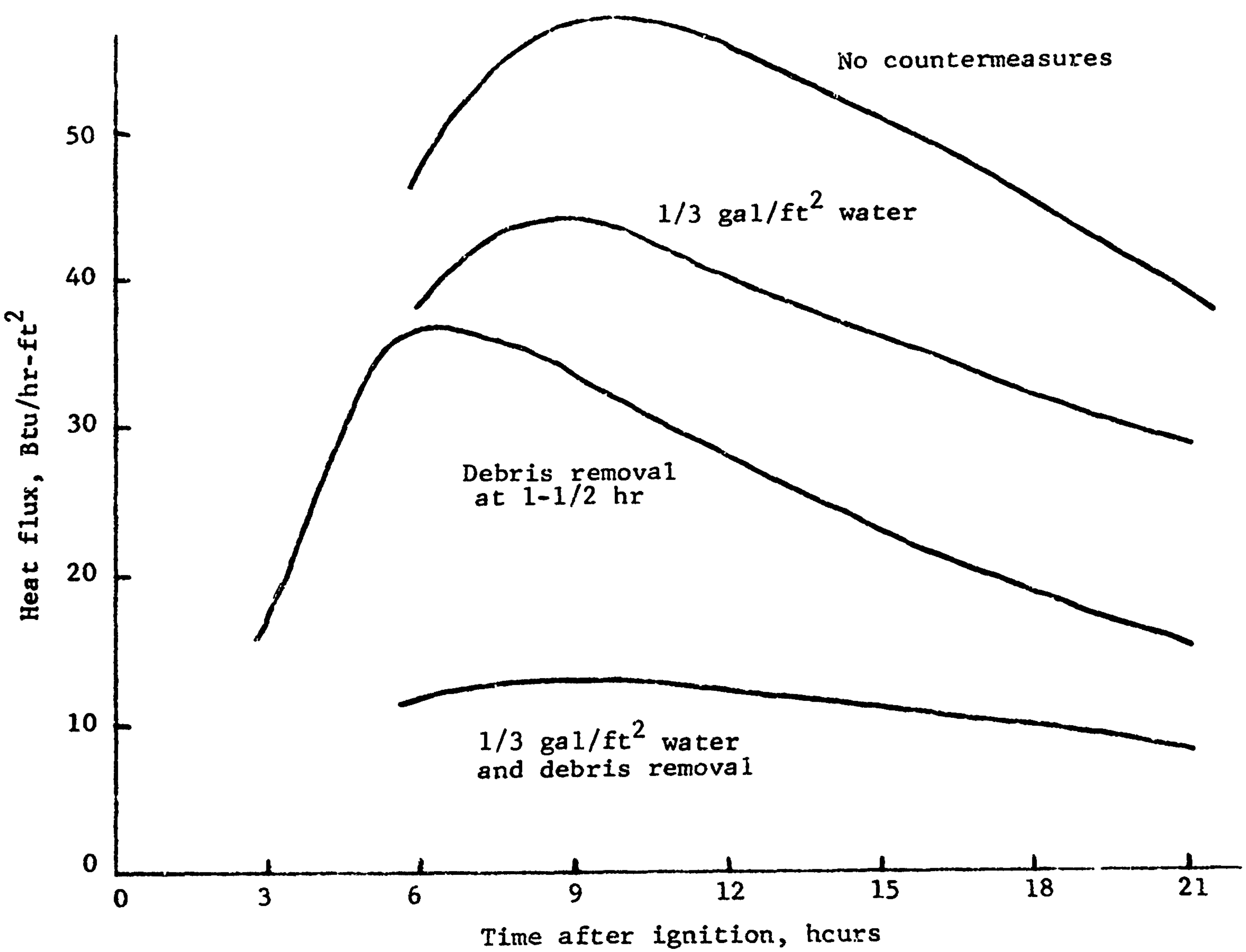


Fig. 7 EFFECT OF COUNTERMEASURES ON CRIB-DEBRIS FIRES OVER 12-in.-THICK SLAB

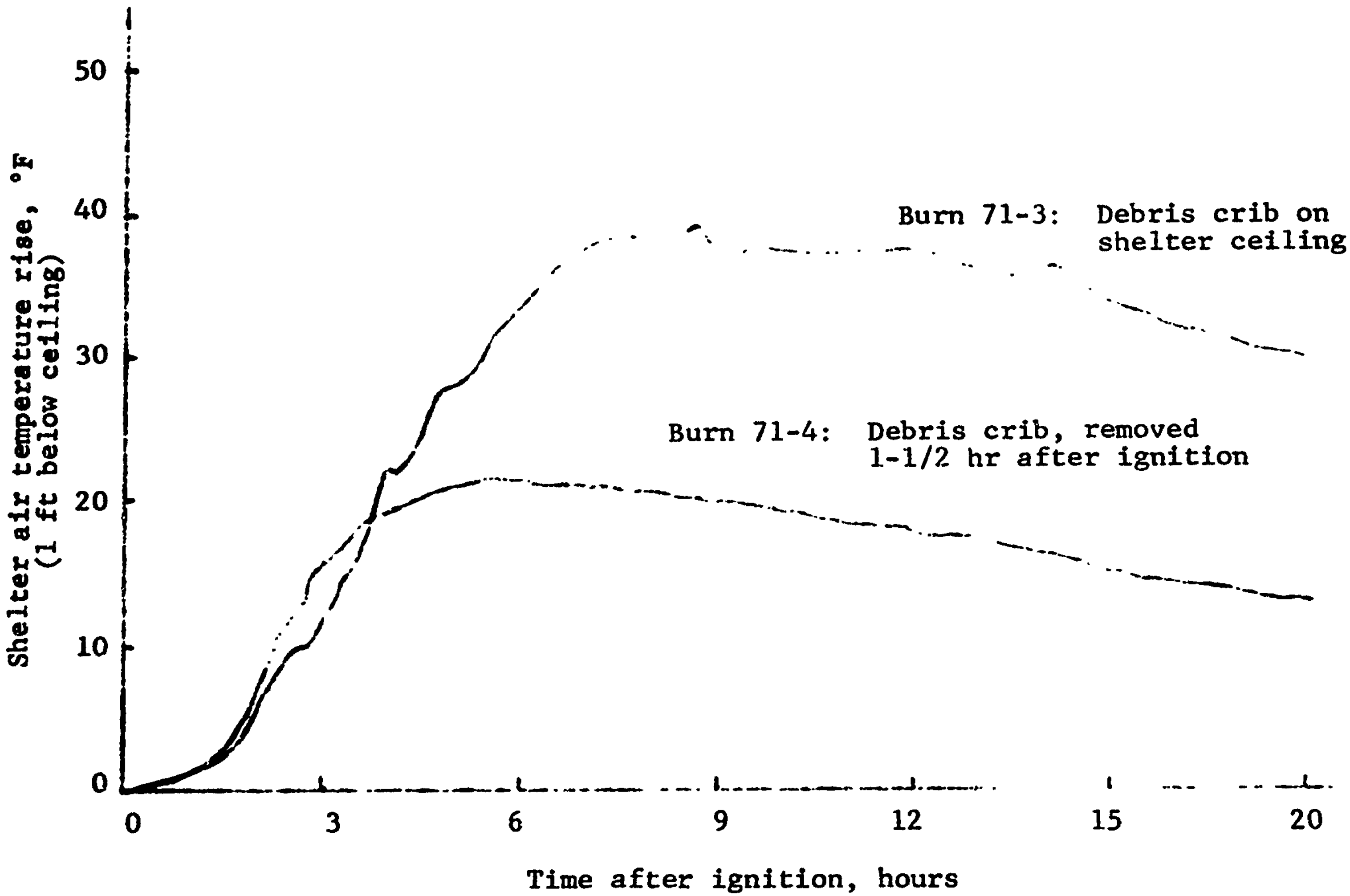


Fig. 8 EFFECT OF DEBRIS REMOVAL ON SHELTER AIR TEMPERATURE

As mentioned earlier, the water was added to one section (6 ft x 6 ft) of the 12-in.-thick shelter ceiling in both experiments using the debris crib. In the first case, water was added over a period of 3/4 hr while in the second case it was added in a matter of minutes. In both cases, the total amount added was 12 gal (1/3 gal/ft^2). Temperature records indicate that the water did not spread over the entire area zoned for it. Upper surface temperatures off to the side of the delivery point showed almost no change as the water was added. Those somewhat deeper in the slab showed the cooling effect at later times. However, the results of 71-3 and 71-4 do not yield all of the hoped for input to aid the mathematical model, and further experiments were conducted using the debris crib and a modified version of it on top of an aluminum plate. These small-scale experiments are described in Appendix C.

4.3 Water Migration in Ceiling Slab

Section 2 describes a set of pans that were attached to the shelter ceiling to selectively collect water driven as steam or as liquid from the lower surface of the shelter ceiling. These have shown no measurable collection through the 12-in.-thick slab during residential debris fires and only small amounts through the 5-in.-thick slab. However, the debris crib fire, a more severe exposure, drove significant amounts of liquid and vapor through both slab thicknesses. The amounts are summarized in Table III. When more data are collected, they will be incorporated into an upgrading of the mathematical description of heat and mass flow in the shelter ceiling slab. At present, it should be pointed out that the vapor, in particular, represents a significant introduction of heat into the shelter space. This heating is not accurately monitored by the heat flow meters as it tends to move around them.

Table III

SUMMARY OF WATER COLLECTED FROM SHELTER CEILING

Experiment	Debris	Time after Ignition	Total Water Collected, lb/ft^2 *			
			12 in. Slab		5 in. Slab	
			Liquid	Vapor	Liquid	Vapor
71-5	Residential	6 hr - 20 min	0	0	0	0.002
		23 hr	0	0	0	0.002
71-6	Residential	6 hr - 15 min	0	0	0.0018	0.0045
		25 hr	0	0	0.0018	0.0045
71-3	Crib	2 hr - 14 min	0**	0**	0.157	0.075
		3 hr - 56 min	0	0.005	0.240	0.183
		5 hr - 30 min	0.002	0.016	0.259	0.206
71-4	Crib	1 hr - 55 min	0	0	0.068	0.015
	(Removed at 1 hr - 30 min)	4 hr - 5 min	0	Trace	0.077	0.041
		6 hr - 5 min	0	0.011	0.077	0.044
		7 hr - 40 min	0	0.011	0.077	0.044

*Water collected during intervals can be calculated by differences. It is planned to gather data at more frequent intervals in future tests.

**Rest of 12 in. slab showed visible moisture except in vicinity of collection point.

4.4 Toxic Gases

4.4.1 Contained Debris Fires

As described earlier, experiments 70-1 through 70-6 (see Table I) considered debris created by the contents and interior partitioning of various occupancies. The blast was assumed to be less than that required to destroy the exterior walls and the debris was essentially contained within the structure. For these conditions, none of the CO or CO_2 concentrations found in the shelter, its entry walls, or at any expected vent locations would be considered significant to a ventilated shelter.

Data from burn 70-6 (library occupancy) indicate a phenomenon that should not be overlooked if total shelter button-up is considered. That is, that although no measurable CO was found outside the shelter, levels inside (near the ceiling) reached 0.015 percent CO approximately 12 minutes after ignition. This would indicate that although the CO concentrations in the combustion products of the burning debris were diluted by the wind as they left the top of the pile, those driven through the "cracks" in the shelter ceiling reached the interior without dilution. As these cracks were quite limited in area, the effect could be greater for other leakage areas and differing winds or structural arrays (wind velocity for burn 70-6 was 10 mph). The total quantity of CO reaching the interior is small and normal shelter ventilation would easily remove it. However, total button-up systems using recirculated air should consider maintenance of a positive pressure in the shelter space and/or means for absorption of CO from the shelter atmosphere.

4.4.2 External Debris and Vent Clearing

Experiments 71-5 and 71-6 were conducted with debris covering the shelter ceiling and an additional 1800 ft^2 of ground surrounding the ramp entrance. The external debris was a uniform distribution that contained about the same combustible loading as that on the shelter ceiling (residential) but a higher percentage of noncombustibles. Appendix B gives the rationale

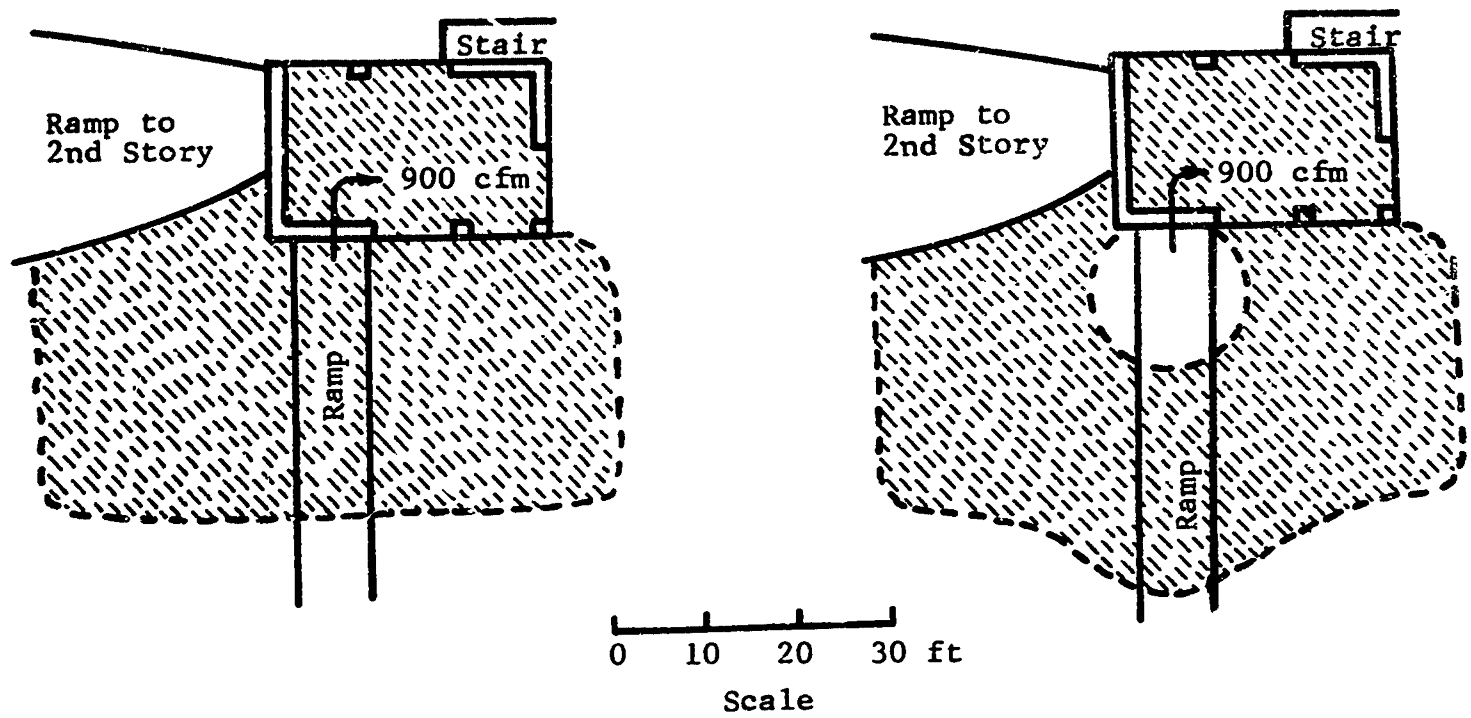
that was applied to developing its description. The external debris used in the experiments did not contain the very large pieces described in Appendix B as they were assumed to have little effect on the gases generated at this shallow level. Obviously, when nonuniform accumulations are considered, these larger items must be added to the deeper piles. For experiment 71-5, debris extended up to the shelter ramp doors, one of which was cut open several feet above the ramp floor to provide an air intake. For experiment 71-6, the debris for a radius of about 15 ft from the intake was removed (and added to the outer perimeter to keep total amount a constant). The debris patterns are depicted in Fig. 9.

Ventilation was continuous throughout each experiment even though it is realized that this would be halted for some period in actual practice. For experiment 71-5, gas concentrations in the shelter rapidly rose to values of 0.35 percent CO at 40 minutes after ignition. At 2 hours after ignition 0.15 percent CO was still being recorded within the shelter space. For purposes of comparison, Table IV presents a summary of physiological effects of carbon monoxide.

The debris clearance of 71-6 ameliorated this condition and a value of 0.04 percent CO was reached at 25 minutes which persisted slightly beyond 1 hour. Thus a problem of toxic gases being drawn into the shelter does exist; can be decreased by debris clearance; but, may be significantly worse for longer burning, larger area debris conditions. This subject will be examined in future experiments.

4.4.3 Increased Debris Depth

To examine the effects of deeper debris piles on burning time and active gas generation, advantage was taken of the ramp entryway to provide a segment of a large pile. The ramp was filled with debris to form piles some 8 ft deep at the shelter doors that gradually reduced (due to rise of ramp) to some 3 ft deep about 24 ft from the shelter.



Experiment 71-5

Experiment 71-6

Fig. 9 DEBRIS DISTRIBUTION AROUND SHELTER INTAKE

Table IV

PHYSIOLOGICAL EFFECTS OF CARBON MONOXIDE*

Carbon Monoxide Content of Inhaled Air percent	Effects
0.02	Possible mild frontal headache after 3 hours
0.04	Frontal headache and nausea after 1 to 2 hours; occipital (rear of head) headache after 2-1/2 to 3-1/2 hours
0.08	Headache, dizziness, and nausea in 45 minutes; collapse and possible unconsciousness in 2 hours
0.16	Headache, dizziness, and nausea in 20 minutes; collapse, unconsciousness and possible death in 2 hours
0.32	Headache and dizziness in 5 to 10 minutes; unconsciousness and danger of death in 30 minutes
0.64	Headache and dizziness in 1 or 2 minutes; unconsciousness and danger of death in 10 to 15 minutes
1.28	Immediate effect; unconsciousness and danger of death in 1 to 3 minutes

* From Ref. 2

The proportions of the debris piles are described in Appendix B. Their total weights are given in Table V. The first of these (71-7) followed the size distribution of Appendix B quite faithfully. The second experiment (71-8) was conducted to examine the magnitude by which a more dense packing and the introduction of entrained soil would extend the burning period or change CO production. For this burn, the brick and blocks of 71-7, now broken into somewhat smaller pieces by the previous fire, were reused with fresh combustibles and plasterboard and 21 ft^3 of fine sand was intermixed as the pile was constructed. The sand was considered to represent both soil and the accumulation of dirt within hidden spaces of the destroyed structure.

In each experiment, the pile was ignited near both ends and at one midpoint. Periodically during the fire, air was drawn in through the intake located some 2 ft above the ramp floor. This attempt to pull shelter air through the debris was used to determine the period where such action is unwise*; but, also to describe that period when the pile was generating significant amounts of gases which, when generated by larger area piles, might provide a general blanketing of the surroundings. In both experiments, the fires produced less heat and more smoke and gases than earlier tests and these gases were observed to hang near the ground for extended distances. They were obviously diluted by the surrounding fresh air as they spread, but this effect would not necessarily be of the same magnitude were the debris coverage over larger areas.

The CO content of the air drawn into the shelter is shown in Fig. 10. The curves were obtained by drawing air for short periods so that adequate measurements were made, and then stopping the airflow so that it would not significantly affect burning of the pile.

*This suggests that the stocking of a simple CO detector would be appropriate so that shelter occupants could monitor ventilation air quality.

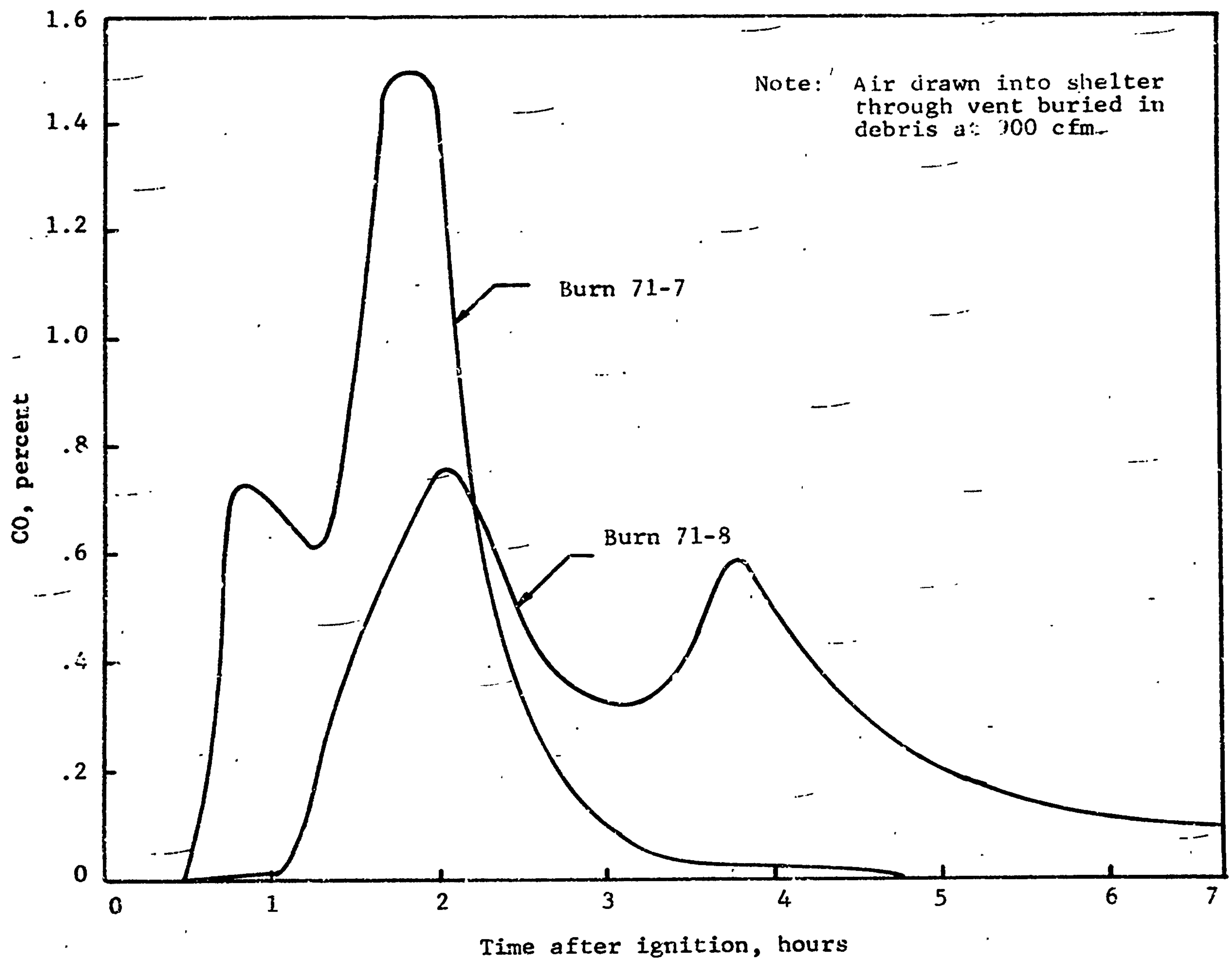


Fig. 10 CO DRAWN FROM DEEP DEBRIS PILES

Table V

DEBRIS LOAD FOR EXPERIMENTS AT INCREASED DEPTH
(71-7 and 71-8)*

Item	Weight, lbs
Residential Combustible Contents	1,477
Residential Noncombustible Contents	665
Plasterboard	1,330
Block and Brick (sizes per Appendix B)	19,810
Structural Wood	812
Total Combustibles	2,289
Total Noncombustibles	21,805

*Load essentially fills ramp entrance to a distance of 24 ft from shelter. It represents slightly over an average of three stories of residential structure but also can be considered to approximate 1-1/2 stories of retail or office building, etc.

The periods of active gas generation can be considered to be about 2-1/2 hours for burn 71-7 and almost 6 hours for the more compact, soil modified pile. The areas under the curves would indicate that the total CO production of the two fires was quite similar. The duration of the fires are such that the active gas generation period usually will precede the period of major shelter heating for thick (12 in.) ceiling slabs. Only in areas where large amounts of unusually deep piles occur should the time overlap be significant. Obviously, one should not attempt to pull air through the debris during the active period and vents for specific shelter buildings should be located so that likely debris patterns for the locale will not cover all vents to the shelter. The impact of having some portion of the total ground area burning in this manner cannot be answered completely until better descriptions are developed of the movement of air and gases over and between areas of burning debris.

5. CALCULATION OF TEMPERATURES AND HEAT FLUXES ASSOCIATED WITH SHELTER HEATING

Here we describe the development of analytical means for calculating shelter temperatures and heat fluxes caused by debris fires. For ease of computations, the analysis was computerized and is currently being used in conjunction with experimental studies to develop a quantitative understanding of the heat transfer mechanisms. This process of cross fertilization will continue throughout the remainder of the program and will culminate in a code for the rapid evaluation of the multitude of attack and environmental conditions that may be conceived. Among the variables of concern are:

- Slab thickness,
- Environmental air temperatures,
- Countermeasures,
- Effects of personnel,
- Effects of ventilation.

We also compare predictions with experimental results to gain an insight into how well the various phenomena are being described analytically and to gain a measure of the importance of countermeasures including their time of implementation. Except for a quantitative understanding of the effects of water application onto the heated shelter, the present analytical description of the heat transfer processes appears satisfactory on the basis of limited checking. Further checking of course, will be performed in the future to ensure the adequacy of the analytical description.

Predictions of the thermal effects of applying either water or removing debris indicate that both countermeasures are effective in very appreciably reducing the shelter heat load.

The remainder of this section is devoted to an elaboration of the above. The first part of this section briefly describes the phenomena and information affecting the transfer of heat

into the shelter; the second part compares predictions with experimental data assuming no countermeasures; and the third part compares predictions with experimental data for the case of water application and debris removal.

5.1 Basic Heat Transfer Information

Heating of shelters caused by burning debris involves a number of important phenomena -- the principal ones being:

- convective and radiative heat transfer from burning debris to top surface of concrete slab,
- heat flow by conduction within concrete slab,
- rate of heat absorption by the boiling of free water within concrete,
- rate of heating of concrete due to condensation of steam within cooler portions of slab, and
- convective and radiative heat transfer from lower surface of concrete slab to the air space within shelter.

Mathematical means for calculating these quantities as well as temperatures of the concrete and air are described in Appendix A. A major simplifying assumption used in the mathematical analysis is that the air space within the shelter is kept sufficiently well mixed to be at a uniform temperature. More detailed calculations involving the stratification of the air temperature are beyond the scope of the present program and, furthermore, are not particularly useful for the real world situation involving people and ventilation. Of key importance for the latter, is a knowledge of the history of the heat flux into the shelter and how it is perturbed by thermal conditions within the shelter.

A summary of quantities used to calculate the heat transfer through and from the concrete are summarized in Table VI and Fig. 11.

Table VI

BASIC DATA USED FOR SHELTER CALCULATIONS

PARAMETER	SYMBOL	VALUE
Density of concrete	ρ	150 lbs/ft^3
Specific heat of concrete	C	0.23 Btu/lb -°F
Thermal conductivity of concrete	K	0.9 Btu/ft-hr-°F
Weight of free water in concrete	P	3 percent by weight
Density of air	ρ_a	0.075 lbs/ft^3
Specific heat of air	C_a	0.24 Btu/lb-°F
Heat transfer coefficient debris to concrete	H_d	10 Btu/ft^2-hr-°F
Heat transfer coefficient steam to concrete	H_w	18 Btu/ft^2-hr-°F per unit depth
Heat transfer coefficient concrete to air space	H_a	1.6 Btu/ft^2-hr-°F

Figure 11 presents an estimate indicating the direction with which water vapor will move after being generated at some depth x_o beneath the heated surface of the concrete. Specifically, the curve indicates the fraction of the vapor $F(x_o)$ moving toward the cooler portion of the slab after being generated at some depth x_o. The function $F(x_o)$ depends on the rate of vapor generation, the resistance presented by the concrete, the differential vapor pressures generated by temperature differences, and has validity only in that along with the heat transfer coefficient H_w, it results in calculated temperatures and heat fluxes in close agreement with experimental data. Basic experimental studies are needed to establish both H_w and $F(x_o)$.

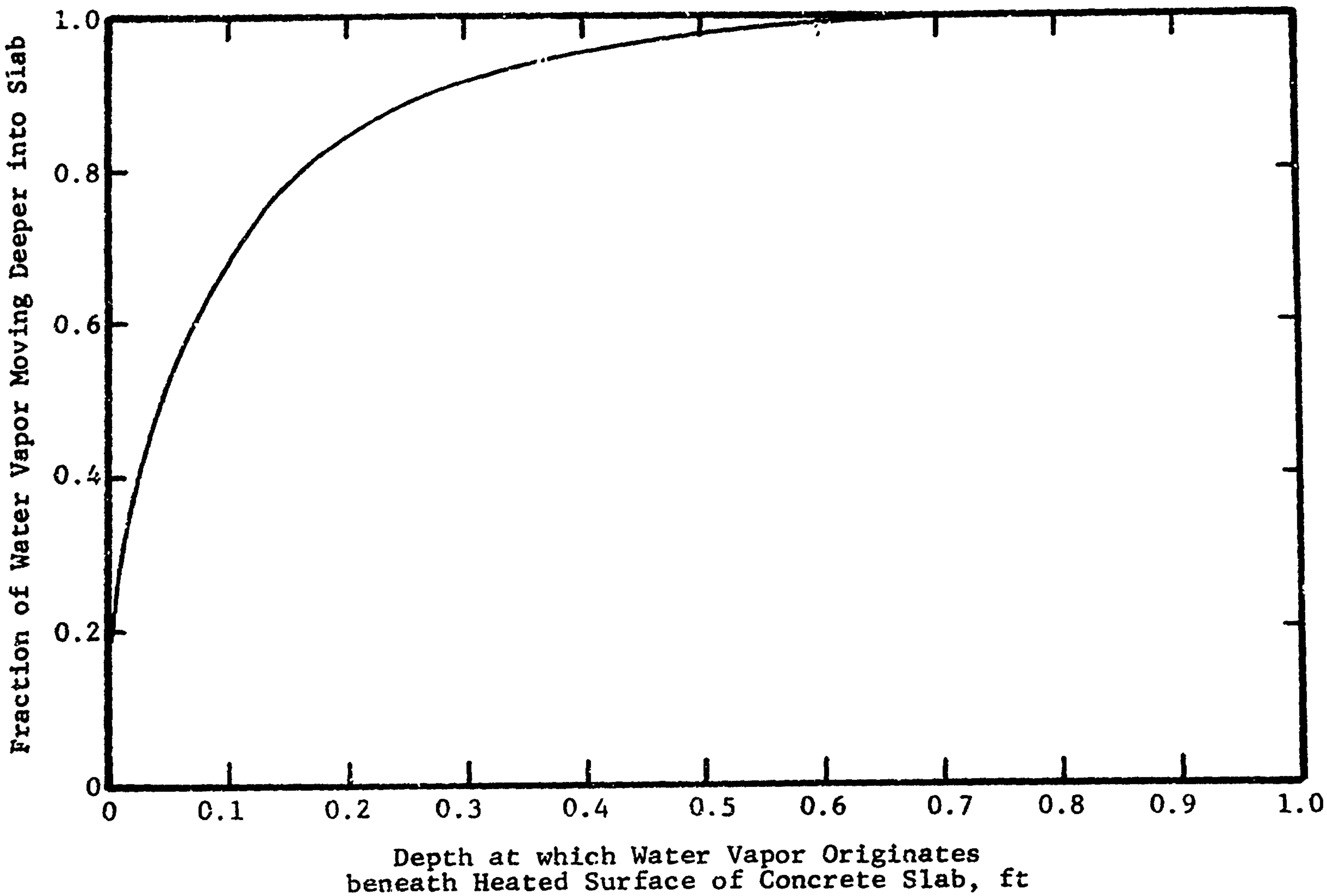


Fig. 11 ESTIMATED FRACTION OF INTERNALLY GENERATED WATER VAPOR MOVING DEEPER INTO CONCRETE SLAB

5.2 Application of Analysis to a Given Experimental Debris Fire

In order to appraise how well the analysis describes the effects of debris fires on shelters, we shall use the results of test 70-2. First it will be necessary to ascertain the rate at which the concrete was heated in test 70-2 and then postulate a mechanism that describes this heating. By using the temperature of the top surface of the concrete slab found in test 70-2 and the analysis of Appendix A, it is possible to determine the temperature history beneath the surface $T(x,t)$ and thereby the heat flux supplied to the concrete $q(t)$ as

$$q(t) = - K \frac{\partial T(x,t)}{\partial x} \qquad (1)$$

where K represents the thermal conductivity of concrete. Figure 12 illustrates the surface temperatures $T(0,t)$ and the calculated heat flux $q(t)$ associated with test 70-2. During much of the early time prior to the peak temperatures, the debris involved appreciable flaming. At later times, the fire became increasingly spotty, followed by glowing reactions and burnout.

Having established the heat flux received from the debris, the next step is to postulate a mechanism that describes this heating. Because of the complex heterogeneous nature of debris piles and of the ensuing fire, detailed analysis is not practical. A more meaningful alternative is to describe the heat flux in terms of the product of a heat transfer coefficient and the difference between the average temperatures of the debris and of the surface of the concrete slab. This of course, introduces two variables, namely the heat transfer coefficient h_d and average temperature of the debris $T_d(t)$, neither of which is known. However if we estimate h_d on the basis of radiation, then it is possible to determine the average temperature of the debris that will produce the heat flux $q(t)$ described in Fig. 12. Using an h_d of 10 Btu/ft^2-hr-°F results in the average debris temperatures shown in Fig. 13. Equation (A-7) of Appendix A describes the resultant boundary condition associated with the heated surface of the concrete. The next step is to check the adequacy of the thermal analysis by first using the results of Appendix A, Table VI, and Figs. 11 and 13 to predict the temperature histories of the concrete and compare these predictions with experimental values.

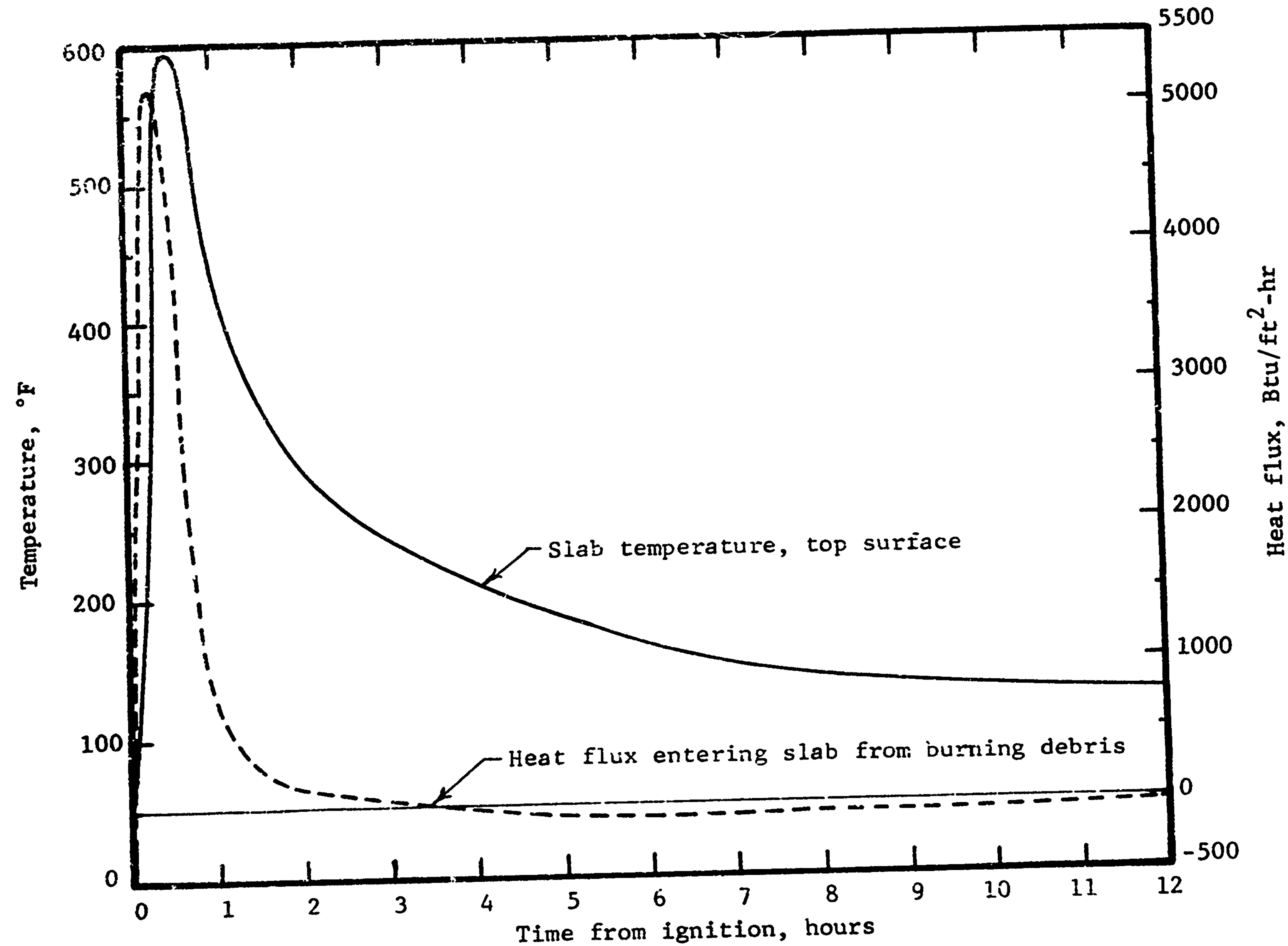


Fig. 12 TEMPERATURE AND HEAT FLUX OF TOP SURFACE OF CONCRETE SLAB

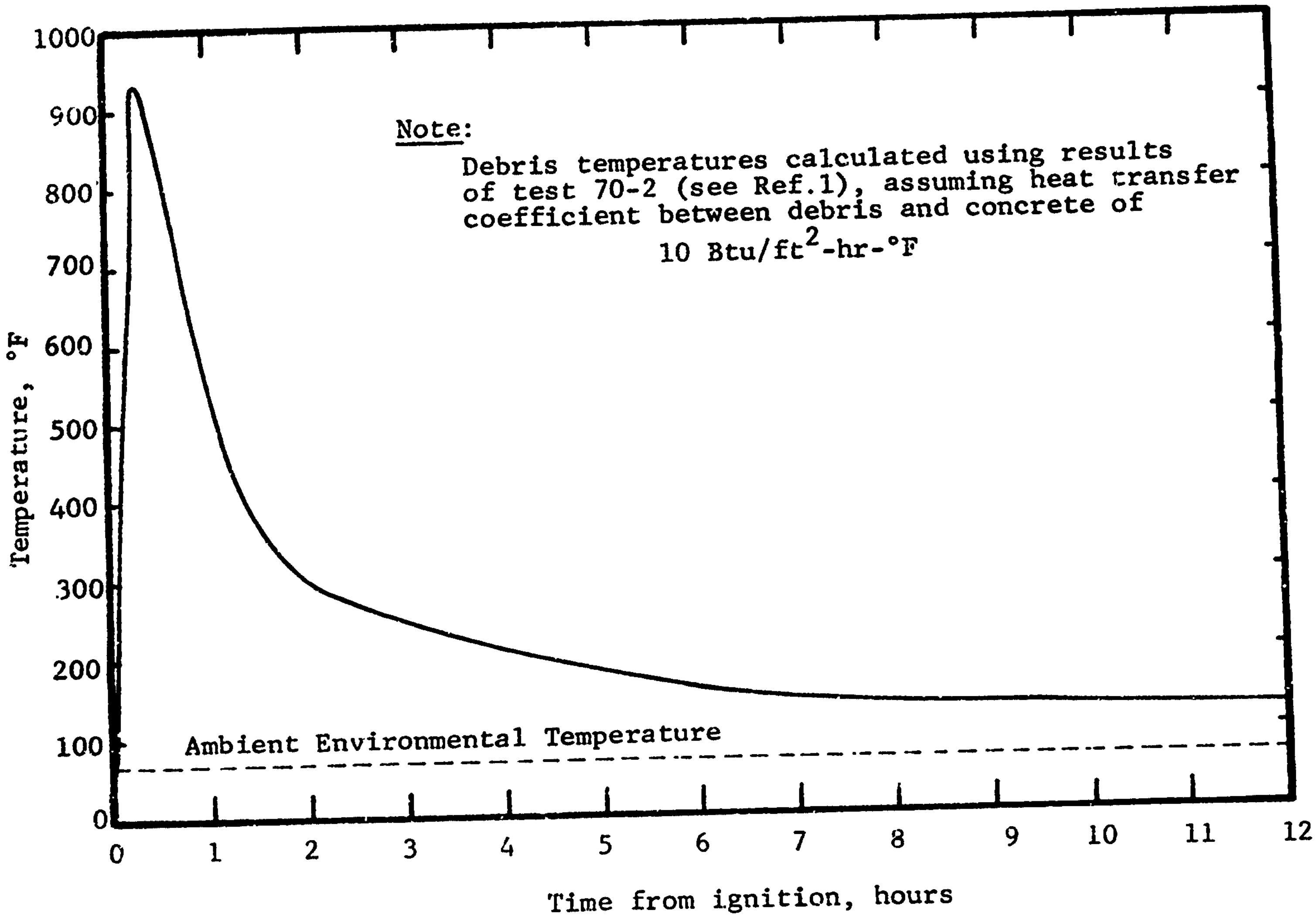


Fig. 13 CALCULATED AVERAGE TEMPERATURE OF DEBRIS IMMEDIATELY ABOVE CONCRETE

As noted earlier, average temperatures will be used throughout this analysis because of the nonuniformity of the heating.

Figure 14 presents a comparison of the calculated and measured temperatures of the bottom surface of the concrete slab over the shelter space while Fig. 15 presents a comparison of the calculated and measured heat flux entering the shelter space. It may be noted that the temperatures are in fair agreement while the flux is in good agreement. Much of the discrepancy in the concrete temperatures may be attributed to uncertainties in the average concrete temperature caused by variations in the concrete temperatures on a point by point basis.

5.3 Effects of Debris Removal and Water Application

Very important reductions of concrete temperatures may be achieved either by removing the hot debris and/or by applying water to the surface of the heated concrete. In order to determine the effect of the two countermeasures on the thermal conditions within the shelter, we must first consider each of the two phenomena.

Debris removal, of course, exposes the upper surface of the concrete slab to the environmental air that may or may not be heated as a result of exposure to other fires following a nuclear attack. Heating of the environmental air will depend on the makeup of the local and surrounding areas, on the severity of the attack, and time. In order to gain an insight into the importance of ambient air temperatures following debris removal, we will consider two situations -- one in which the air remains at ambient temperatures and one in which the air is sufficiently hot so that the concrete loses no heat to the environmental air.*

*This also represents the case where ashes and other debris insulate the slab surface.

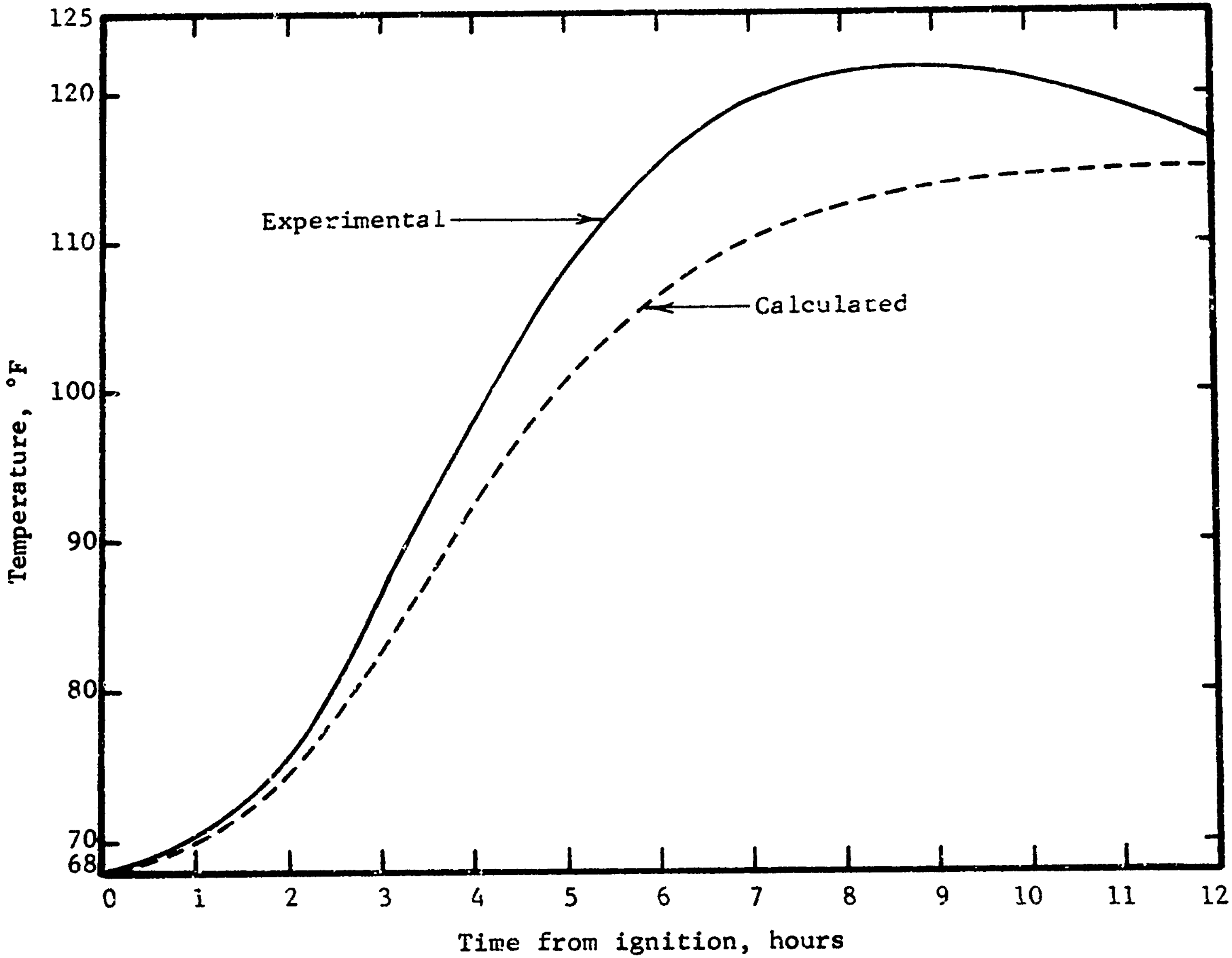


Fig. 14 COMPARISON OF PREDICTED AND EXPERIMENTAL TEMPERATURES OF SHELTER CEILING

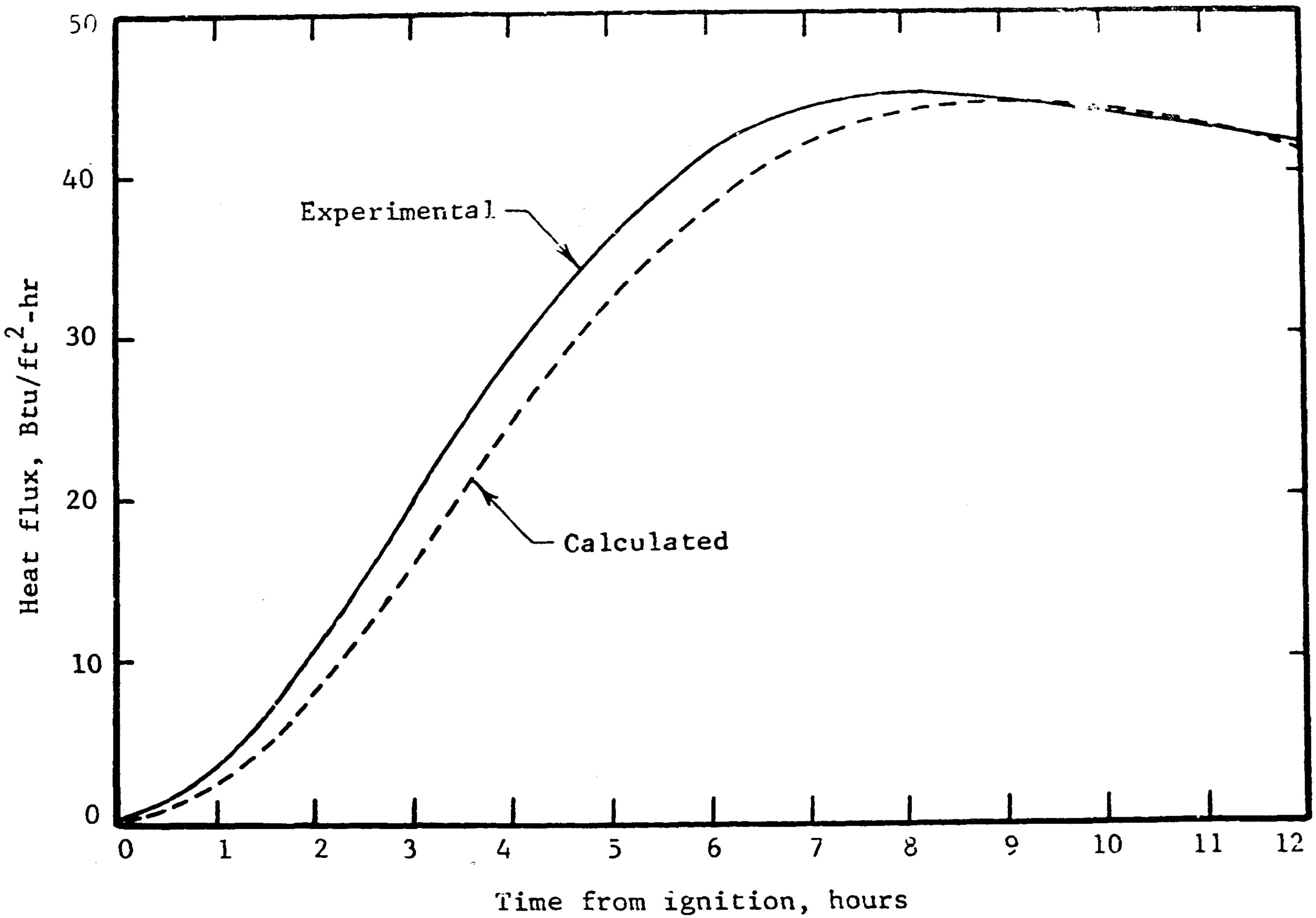


Fig. 15 COMPARISON OF PREDICTED AND EXPERIMENTAL HEAT FLUXES INTO SHELTER

For the case in which heat is lost to the environmental air, the boundary condition may be described as

$$h \cdot (T(0,t) - T_o) = K \left. \frac{\partial T(x,t)}{\partial t} \right|_{x=0} \qquad (2)$$

where:

h	=	heat transfer coefficient between top surface of concrete slab and the environmental air,
$T(x,t)$	=	temperature of concrete at depth x and time t,
T_o	=	ambient temperature of environmental air, and
K	=	thermal conductivity of air.

This equation should be used in place of Eq. (A-7) after the debris is removed. For the case of no heat flow one should set the left-hand side of Eq. (2) equal to zero.

The next problem is how to treat the effects of water application. In addition to cooling the surface of the concrete, water will affect the fire intensity to some unknown degree. However, at this point it is difficult to quantitatively appraise how the fire will be affected by the water and more importantly how the heating will be altered. Therefore, in the interest of being conservative, we will proceed for the time being as if the effect of the water on the debris is negligible and consider only the cooling effect of the water on the concrete slab. Heat flux into the slab will be maintained as described by Eq.(A-7) of Appendix A at the same time the surface is being cooled by water. As a result, actual benefits of water application on moderating peak shelter heating will be somewhat greater than the predictions since the water will extinguish and cool some of the burning debris and thereby act as a buffer to heat flow from the debris. Preliminary analysis of experimental data indicates that such a buffer is most effective in retarding heating and requires closer examination in future studies.

Here the results for four different situations are examined, namely:

(1) No countermeasures

(2) Application of a total of 1/3 gal of water to each square foot of heated surface during the 10 to 34 minute period following start of the debris fire.

(3) Removal of hot glowing debris 30 minutes after start of the debris fire.

(4) Combined approach involving water application and debris removal; water is started immediately after the debris is removed at 30 minutes.

In all cases the application of water is continued for a duration of 24 minutes consistent with that of experiments 71-1 and 71-2. Thirty minutes was chosen as a suitable time for debris removal since much of the flaming is down for this fire by 30 minutes and the environment presented by the debris appears to be tolerable to personnel.

Figure 16 presents the effect of a residential type debris fire (test 70-2) on the shelter for the case of no countermeasures while Figs. 17, 18 and 19 illustrate the anticipated effects of water application, debris removal and a combination of these countermeasures, respectively. First, Fig. 17 indicates that the slab cooling effect from water application significantly reduces the temperature rise and heat flux into the shelter apart from any debris cooling or extinguishing effects. Results from test 71-2 involving similar water application were much more impressive than that shown in Fig. 17 and suggest that the effect of water on the hot burning debris is much more than just the cooling effect of water on the concrete.

Second, it may be observed from Fig. 18 that the removal of debris at 30 minutes also appreciably reduces the temperature and heat flux. The shaded areas shown in Fig. 18 represent the range of values that may occur depending on the ambient temperature of the environment.

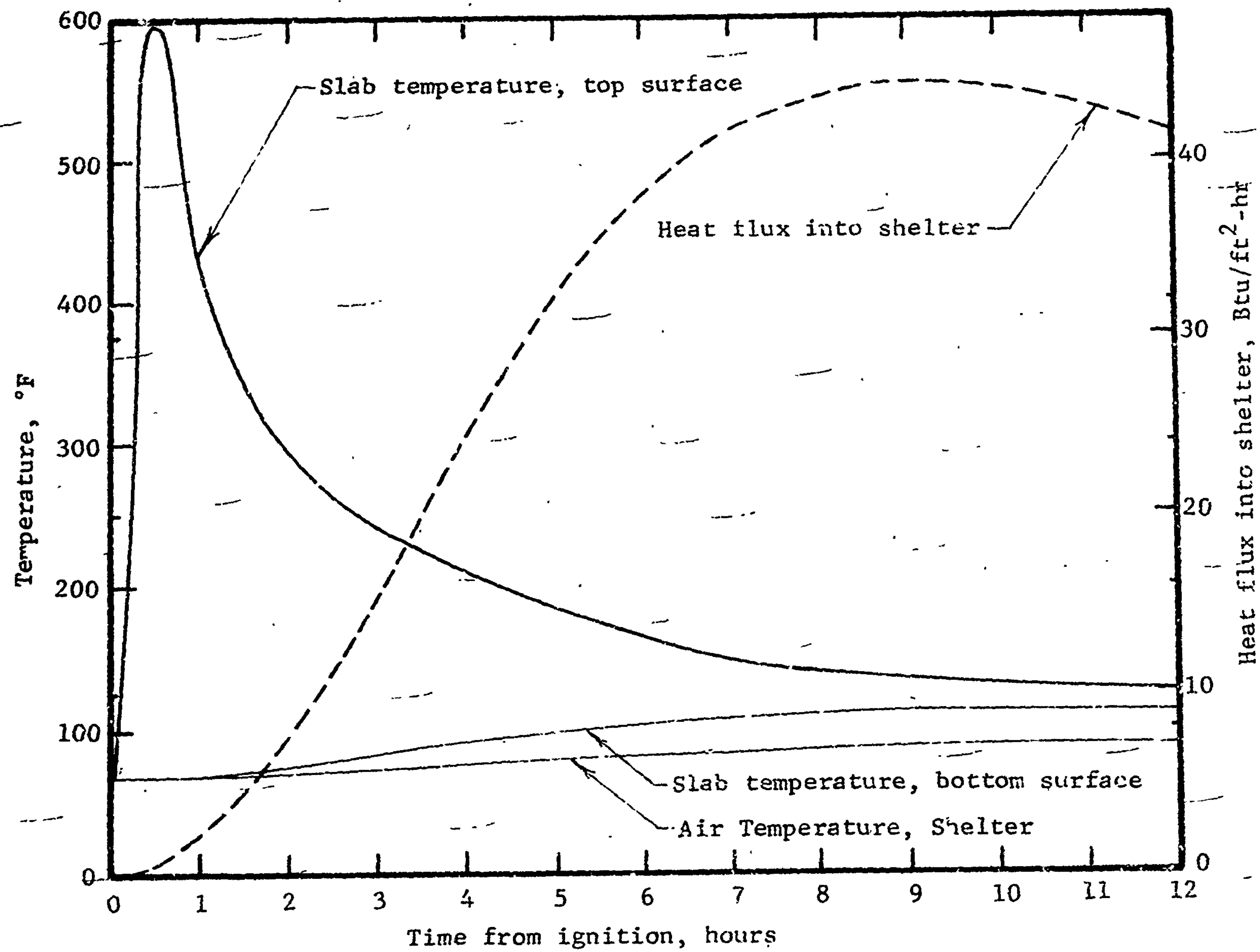


Fig. 16 SHELTER CALCULATIONS: NO WATER DELUGE OR DEBRIS REMOVAL

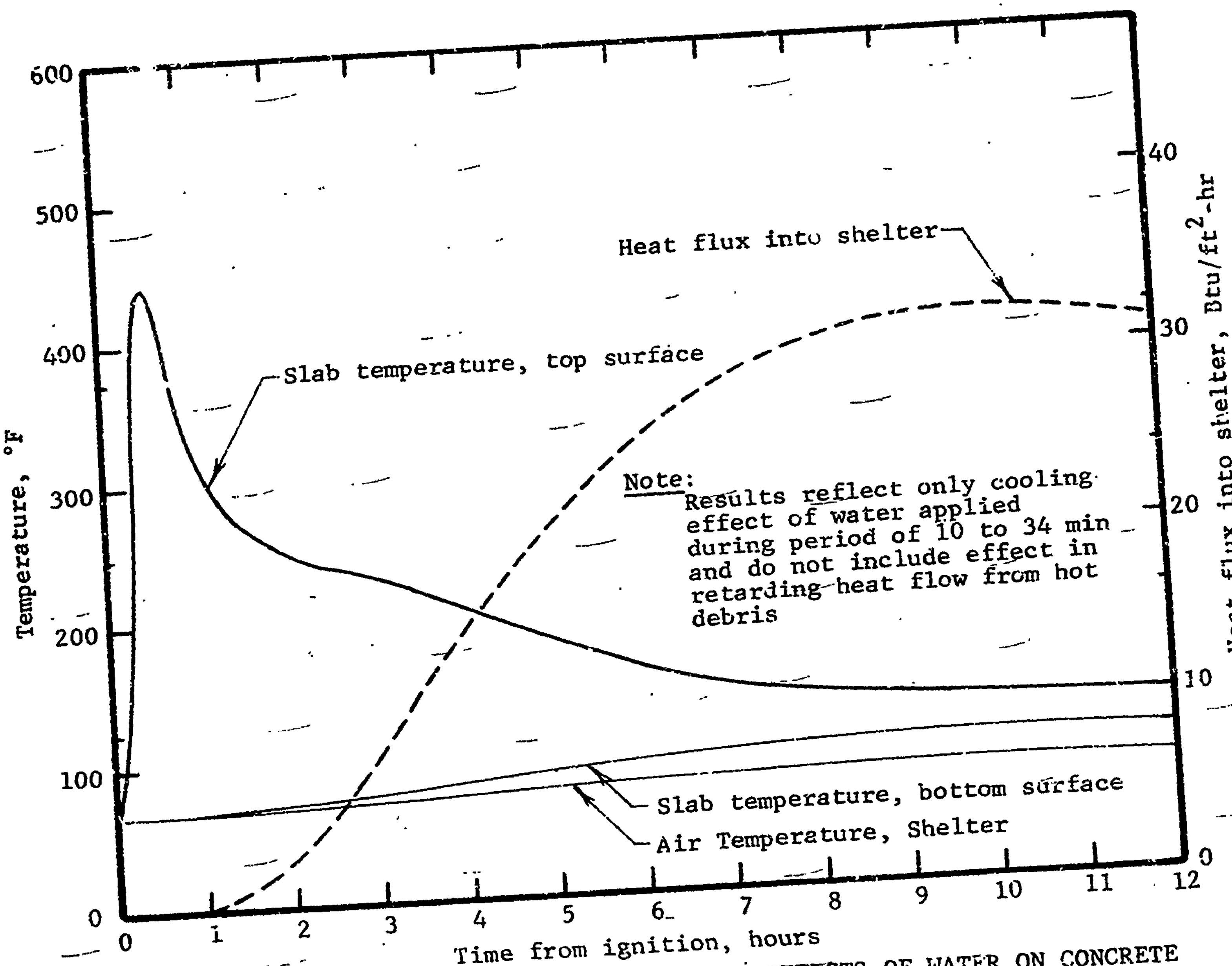


Fig. 17 SHELTER CALCULATIONS: COOLING EFFECTS OF WATER ON CONCRETE APART FROM EFFECT ON DEBRIS

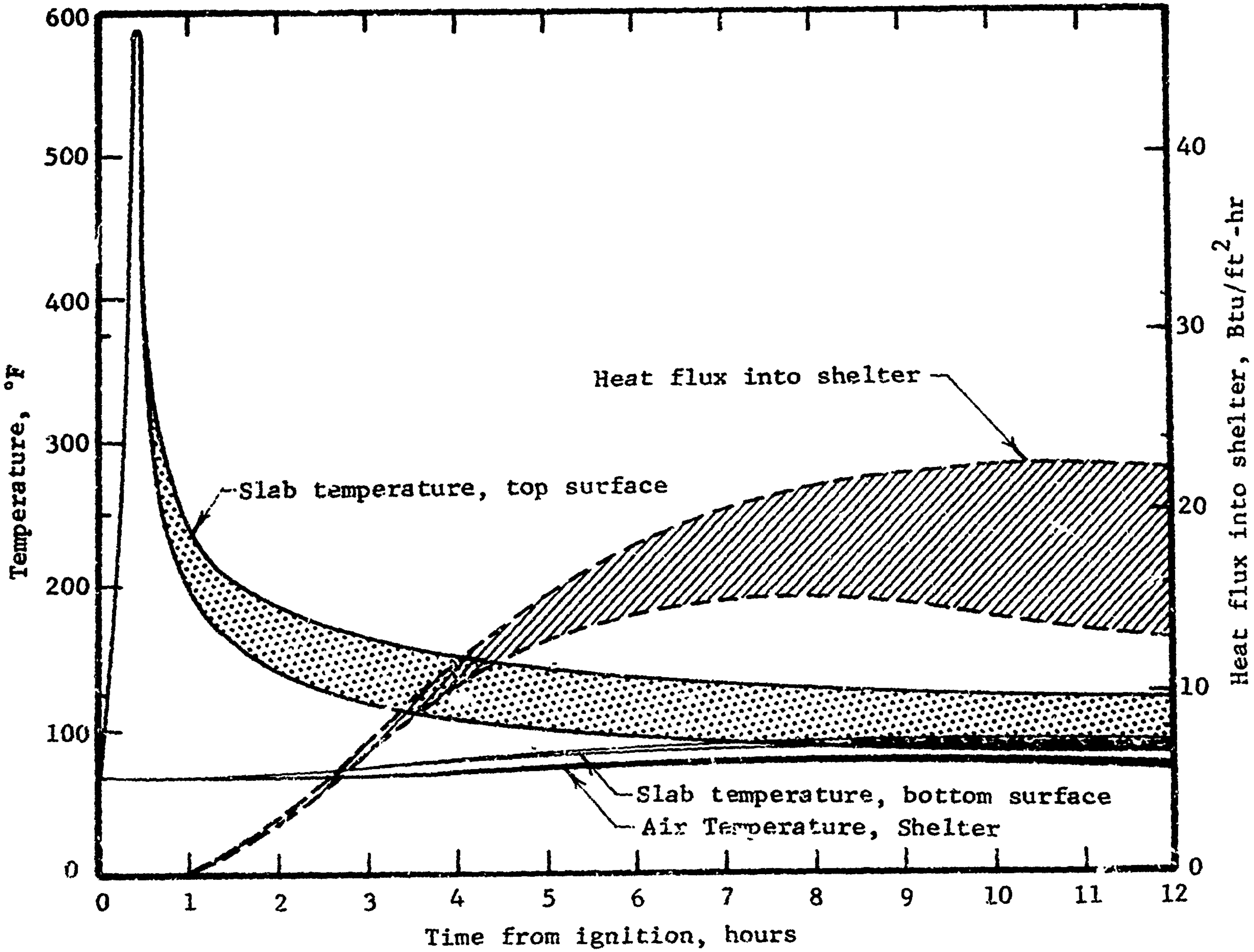


Fig. 18 SHELTER CALCULATIONS: DEBRIS REMOVAL AT 30 MINUTES

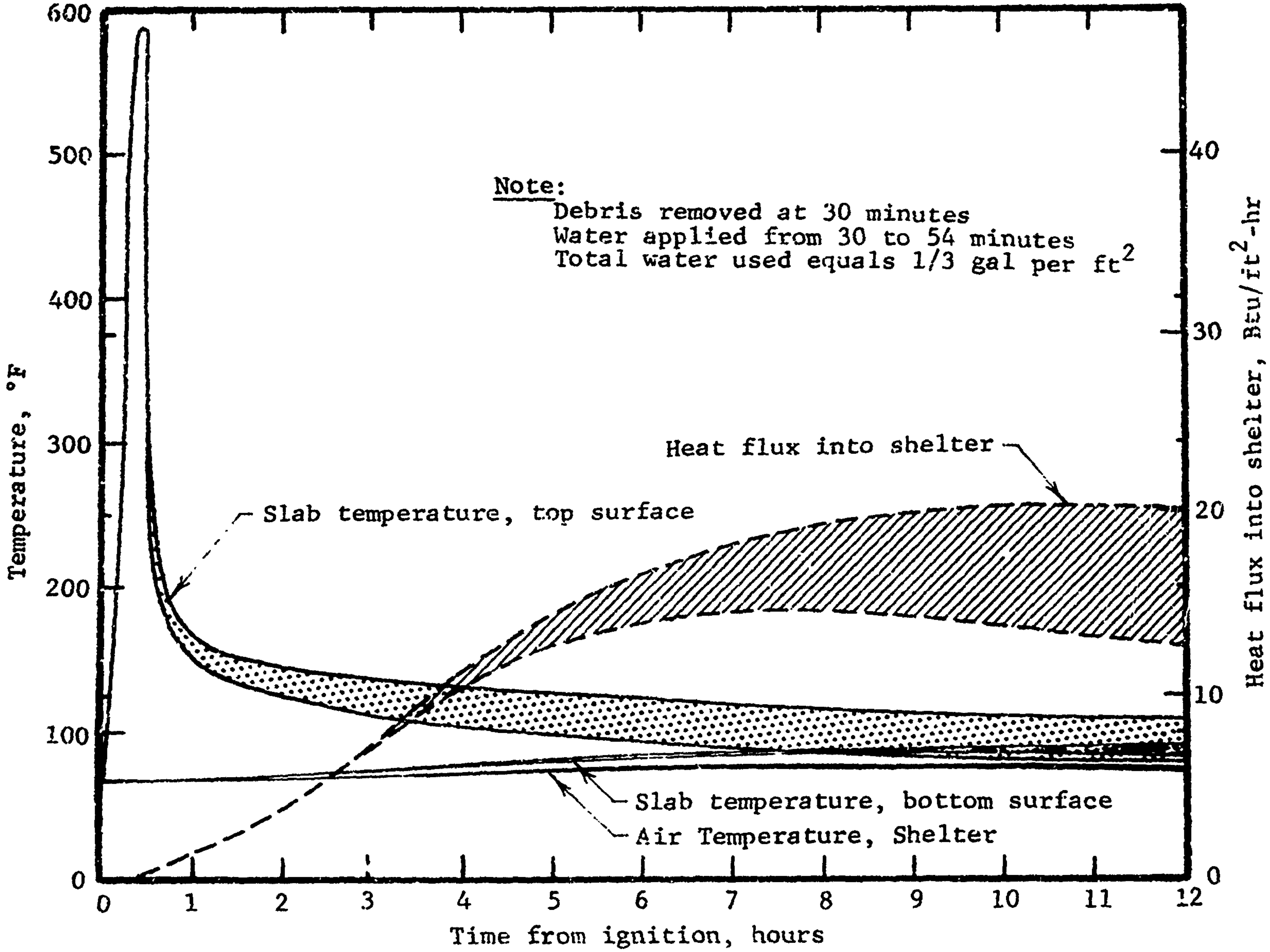


Fig. 19 SHELTER CALCULATIONS: WATER DELUGE IMMEDIATELY FOLLOWING DEBRIS REMOVAL

The lower bound represents values that would be achieved as a result of heat losses to environmental air at normal temperatures while the upper bound represents values for the case in which the concrete neither loses nor gains heat following debris removal. For the case of normal environmental air temperatures, the peak flux of 15.2 Btu/ft^2-hr occurs at 8 hours while the 7°F maximum rise of the average air temperature occurs at 10 hours. For the case of no heat loss, the peak flux of 22.7 Btu/ft^2-hr occurs at 11 hours while the maximum rise in the air temperature of 11°F occurs at 12 hours. These values may be contrasted to the calculated values of 44.3 Btu/ft^2-hr (9 hours) and 21°F (12 hours) for the case of no countermeasures. These results are particularly impressive when one realizes that the fire environment is probably tolerable to debris removal even without protective clothing after 30 minutes.

Figure 19 illustrates the effect of removing the debris at 30 minutes and immediately applying 1/3 gal/ft^2 of water over a period of 24 minutes. As in the previous figure, the lower bound of each shaded area represents the case of normal environmental air temperatures while the upper bound represents the case of no heat losses from the upper surface of the concrete slab. The peak flux into the shelter for the case of cool ambient air is 14.8 Btu/ft^2-hr and occurs some 8 hours after the start of the debris fire. This flux may be contrasted with the value of 44.3 Btu/ft^2-hr obtained for the case of no countermeasures shown in Fig. 16 and the flux of 12 $\pm$ 2 Btu/ft^2-hr measured in test 71-2 when an identical quantity of water was applied between 35 and 49 minutes following the start of the debris fire.

Figure 20 illustrates the effect of the time of debris removal on the maximum average temperature of the air within the shelter and on the maximum heat flux entering the shelter space. As before, the lower bound of each shaded area represents the values that may be expected with normal environmental air temperatures while the upper bound represents cases of heated environmental air in which there are no heat losses following debris removal.

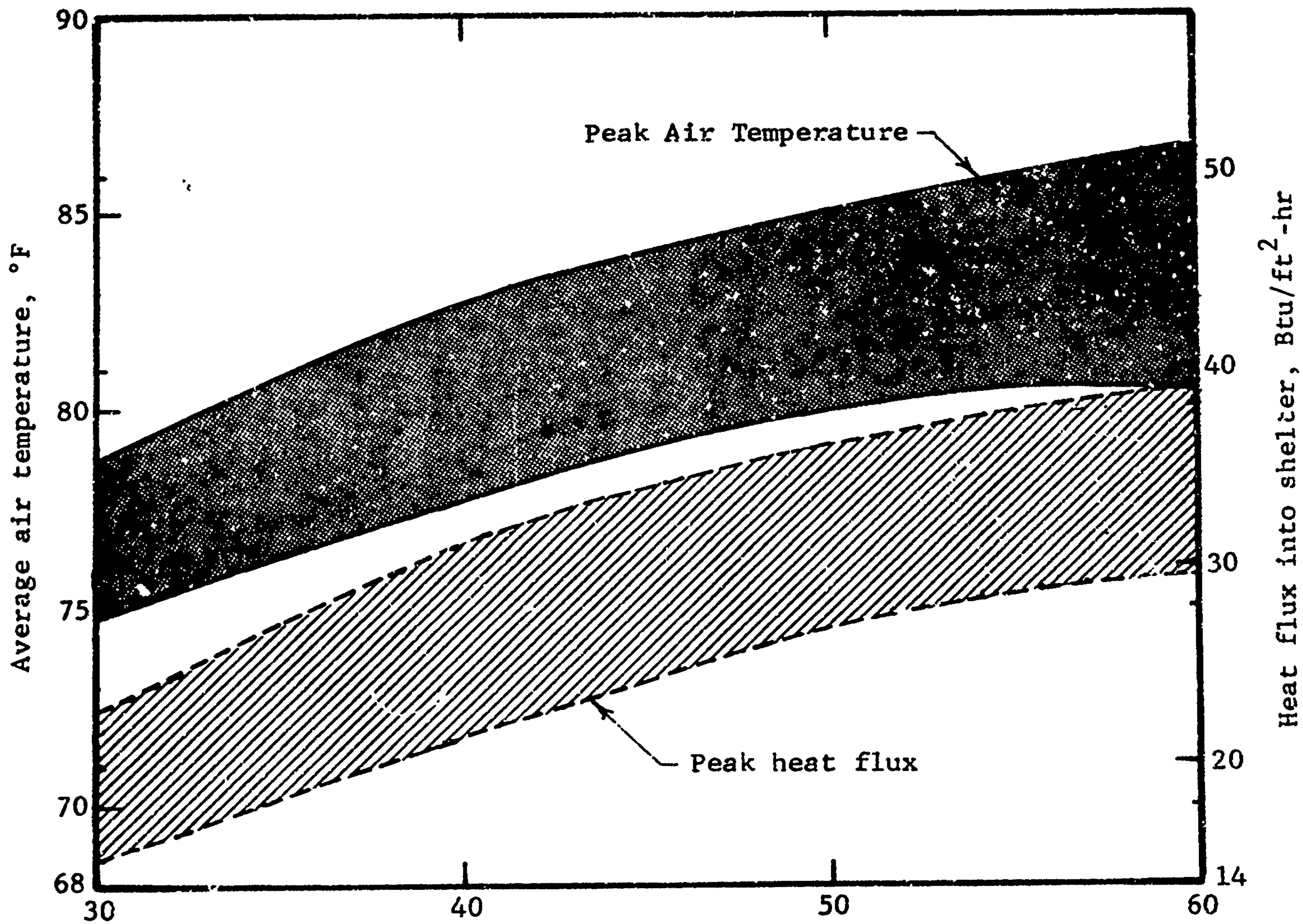


Fig. 20 EFFECT OF DEBRIS REMOVAL ON PEAK FLUX AND AIR TEMPERATURE OF SHELTER

It may be observed that both the air temperature and heat flux increase appreciably the longer the debris removal is delayed. After a few hours, removal of residential type debris such as employed in tests 70-2, 71-1 and 71-2 ceases to be effective.

5.4 Steam Generated within Concrete

Steam generated by the excessive heating of free water within concrete has two adverse effects. The first is to transfer heat absorbed from the hotter portions of the concrete to cooler regions near the shelter space by vaporization and condensation; and the second is to transfer heat directly into the shelter space if the concrete slab is too thin to totally condense the evolved water vapor. If the latter occurs, the combination of heat and humidity load on shelter inhabitants could be significantly increased during the early fire period.

Fortunately, in no cases did significant quantities of water vapor penetrate the 1-ft-thick concrete slab. The maximum penetration of the vapor predicted by the calculations was 0.8 ft for the residential debris load and is consistent with the fact that no water vapor was collected in tests 71-1 and 71-2 on the underside of the 1 ft slab. However, the calculations suggest that water vapor may penetrate concrete slabs significantly less than 0.8 ft thick, in particular, at increased fuel loads and, if so, could seriously increase the heat load within the shelter space. Work, of course, needs to be performed to check out this possibility.

6. SUMMARY AND CONCLUSIONS

Here we shall summarize what is known about debris fires as well as countermeasures to reduce the effects of excessive heat or toxic gases on shelter occupants. Included is a specification of areas of major ignorance that require resolution to identify optimally effective means for coping with such fires. While major inroads have been and, hopefully, will continue to be made into such areas, it is clear that a number of needs will remain to be resolved at the culmination of the present program.

6.1 Heat Loading

6.1.1 Debris Piles

Generally speaking, fires within residential type debris piles will, within the first hour, deliver their maximum heat flux into a shelter of a few thousand Btu per sq ft and rapidly subside thereafter. Peak heating of the shelter interior will occur several hours later. For situations involving relatively cool environmental air temperatures, the heat flow into the concrete will reverse direction after several hours and transfer substantial quantities of heat from the concrete slab to the external environment. A total of a few thousand Btu will be absorbed by each square foot of heated surface during the several hours following fire start. This sequence of events is appropriate to other occupancies although with modified time scales.

Experiments have shown that heat loading of an unventilated shelter through a 12 in. ceiling slab by a residential debris fire equals that of the expected occupants. For a 5 in. slab, the heating reaches an equivalent of four added occupants per shelter space. Where less blast damage or less blanketing types of noncombustibles permit freer burning, heat loading of the shelter is reduced. Higher fuel loadings produce increased but not proportional heat loads on the shelter. A library

loading with heavy masonry partitioning produced the equivalent heating of 2-1/2 occupants per space through a 12 in. slab and 7 occupants per space through a 5 in. slab.

At present there are two recognized areas of ignorance for projecting the measured results to other situations. The first is a poor quantitative understanding of the mechanisms dominating the transfer of heat from burning debris to the concrete, and the second is a poor quantitative understanding of how this heat flow is affected by the application of water onto the heated concrete. Detailed mechanistic descriptions, while most satisfactory, are impractical at the present time. A more attainable goal utilizes empirical means that describe the heat flow in terms of temperature difference between the debris and concrete.

6.1.2 Slab Thickness

The thickness of the concrete slab is of key importance in affecting not only the magnitude of the heat flux into the shelter space but also the times at which the peak fluxes occur. Thin slabs result in increased heat transfer through the slab by conduction and by the vaporization and condensation of free water, produce more severe heating of the shelter and cause it at earlier times when ventilation air may be restricted. The result, of course, will be a more rapid and pronounced increase of the heat load within the shelter that will be especially serious if appreciable quantities of steam penetrate the thin slab. Accurate predictions of the effect of slab thickness will be possible once the present computerized analysis is completely checked out. Otherwise, there are no significant obstacles involved in making such predictions.

6.1.3 Water Vapor

As noted earlier, the importance of the generation and movement of water vapor within concrete has important effects on the transfer of heat into the shelter space. Because of the limited range of temperatures experienced by the concrete on

exposure to debris fires, practically all of the evolved water will be free water. Since the amount of free water in concrete will vary with the humidity, conditions of high humidity are conducive to increased heating of the shelter space.

At the present time, the internal generation of water vapor is being described as a boiling process that occurs at increasing depths within the concrete. Practically all of the evolved vapor is released within the first hour for the 1-ft-thick concrete slab of test 70-2 and involves free water within the first few inches of concrete. Part of this water vapor escapes through the heated surface of the concrete; part is condensed out at deeper and cooler depths within the concrete; and part will enter the shelter in cases of thin slabs and/or intense, long duration debris fires.

Hopefully, more data will be forthcoming from future tests with the slabs instrumented to check the present description used to predict the effects of water vapor. Most information will come from collection of water vapor that passes through the 5 in. slab and comparison of its weight with that predicted by the present analysis. Limited experimentation with a slightly thinner slab is also being considered.

6.1.4 Initial Temperature

Even though no studies have been undertaken to appreciate the effect of the initial temperature, one can at least to the first order approximation consider that any reasonable temperature variation either up or down will be additive on the shelter temperatures. Temperature variations are not expected to be large especially since building temperatures are usually held within narrow ranges.

6.2 Countermeasures Applied to Shelter Ceiling Slab

A variety of countermeasures may be used to diminish the consequences of debris fires on the shelter ceiling. Here we

will limit discussion to postattack actions such as the removal of hot and burning debris and the application of water. Experimental evidence indicates that application of an average of 1/3 gal of water per ft^2 of heated surface at about 1/2 hour following the start of a residential debris fire will reduce the peak heat flux into the shelter to values about one-fourth that without water. Similar reductions of temperature rises and heat fluxes to the shelter are predicted by analytical means if the debris is removed 1/2 hour after ignition.

Predictions of the effect of debris removal present no difficulties presuming a knowledge of the subsequent environmental air temperatures. Heated environmental air, of course, could have serious consequences on shelter inhabitants if it is sustained for many hours.

At present, predictions of the effect of water application suffer from a lack of knowledge of the quantitative effects of water in altering heat flow to the concrete slab due to cooling and extinguishing of hot burning debris immediately above the heated surface of the concrete slab. These answers will be pursued in future experimentation.

6.3 Toxic Gases

Experiments with contained debris (70-1 through 70-6) indicate that localized debris fires of moderate depth do not generate toxic gases for long periods. The debris was representative of that created by the destruction and mixing of interior partitioning and building contents. This type of debris burned with sufficient intensity that the gases generated rose quite quickly and should not obviate a shelter by gas accumulation at ventilation points.

When the debris (interior partitions and contents) extend beyond the structure and surround shelter vents, a period of time exists when the vent cannot be used. Multiple vent locations can often solve this problem or button-up can be considered

since this period usually will occur prior to significant heat loading of the shelter ceiling. Localized clearing of the ventilation intake provides significant benefit (71-5,6) so long as the general air quality of the entire area has not been obviated.

Debris piles of increased depth with a composition representative of destruction of total structures and contents can produce slow burning fires whose gases show a tendency to hang along the ground. Whether or not a large number of such fires over large areas of high building density would cause general blanketing of an area remains to be resolved. Fortunately, recent advancements in the state of the art for the analysis of stratified flow permit combined analytical and experimental assessment of the problem and such study should be initiated. Solution of this problem would define those specific portions of the total urban area where more complex countermeasures might be required as part of effective slanting. In conjunction with this will be the need for means to more rapidly assess actual debris patterns for specific building complexes and attack conditions. This technology exists but needs implementation in the form of a computer code.

Debris directly over the shelter space can cause a toxic gas problem during shelter button-up if wind induced pressures are such that gases are driven directly from the pile down through cracks in the shelter envelope. Where these are minor, shelter pressurization and/or crack sealing can solve the problem. More significantly the phenomenon points to the importance of examining each structure for slanting so that no major flaws are permitted in the continuity of the shelter envelope (unprotected stairwells, shafts, pipe chases).

APPENDIX A

MATHEMATICAL REPRESENTATION OF HEAT FLOW INTO SHELTER SPACE

APPENDIX A

MATHEMATICAL REPRESENTATION OF HEAT FLOW INTO SHELTER SPACE

Concrete can be physically altered in composition by temperature in four ways. In order of increasing temperature, these are:

- loss of free water,
- dehydration,
- calcination, and
- melting.

Loss of free water can occur at any temperature while dehydration, calcination and melting occur at temperatures of 750 to 840°F, 1020 to 1470°F and 2100 to 2300°F, respectively, depending on the composition of the concrete. Since debris fires usually do not heat the concrete slab sufficiently to cause dehydration, calcination or melting, or concern here is limited to the effects of the evolution of free water on the temperature distribution within the slab.

There are basically three phenomena of importance in affecting the distribution of heat within concrete as depicted in Fig. A-1 namely:

- heat conduction,
- boiling of free water, and
- recondensation of water vapor generated by boiling.

Diffusion of free water and the resultant movement of heat are considered to be of secondary importance in affecting the concrete temperatures.

A.1 Transfer of Heat within Concrete

The effects of the conduction and condensation of water vapor on the concrete temperatures may be described by

$$\alpha \frac{\partial^2 T(x,t)}{\partial x^2} + \frac{q_c(x,t)}{\rho \cdot C} = \frac{\partial T(x,t)}{\partial t} \qquad \text{(A-1)}$$

where

α = thermal diffusivity of concrete,

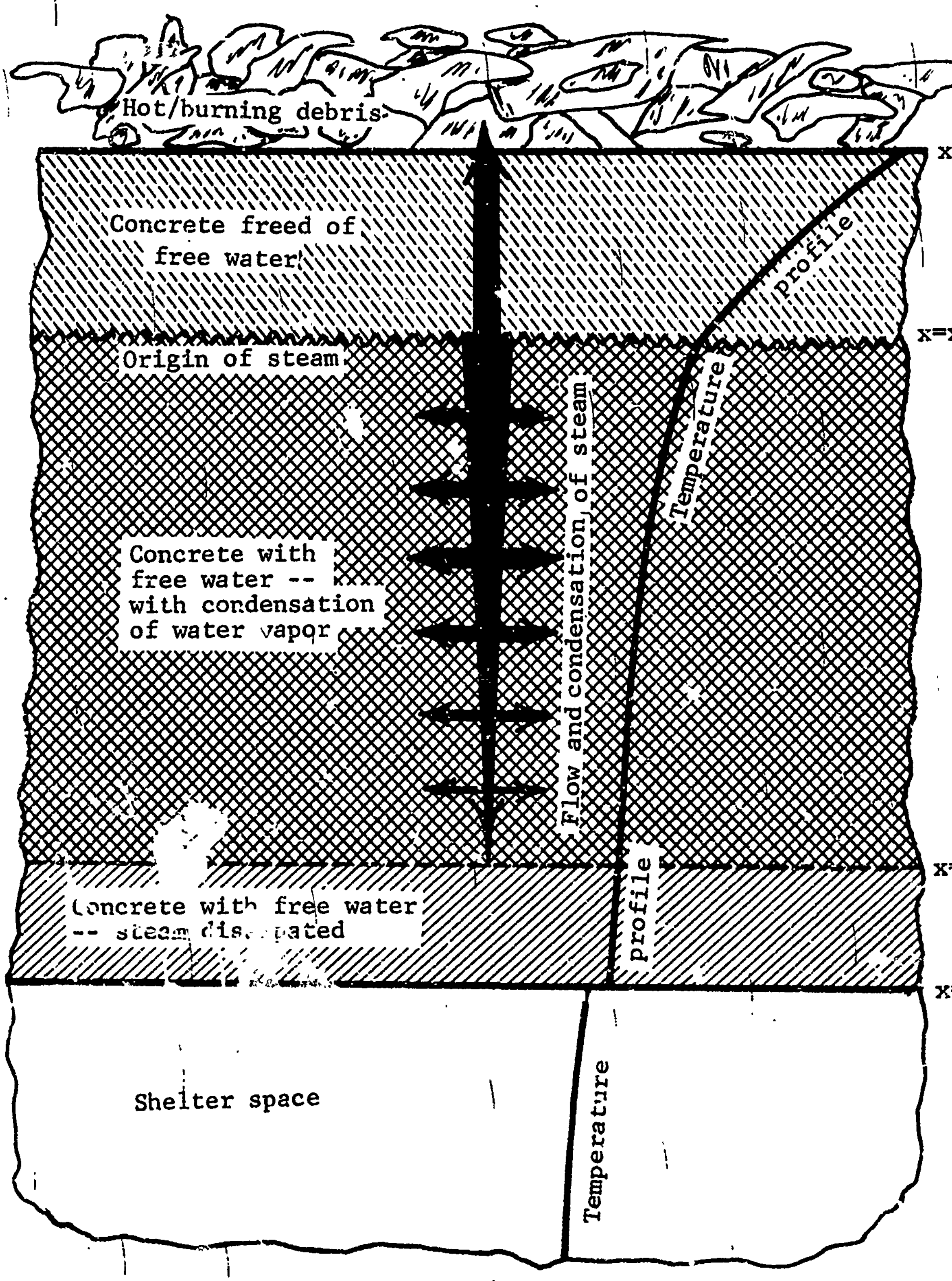


Fig. A-1 GENERATION AND CONDENSATION OF STEAM WITHIN CONCRETE SLAB

x = depth,

t = time,

q_c = rate of heat absorption by condensation of water vapor per unit volume of concrete,

ρ = density of concrete, and

C = specific heat of concrete.

This equation applied only to regions on either side of the zone at which the water is being vaporized. At the upper portions of the concrete slab over the shelter, the concrete temperatures will exceed that of boiling water after a few minutes of heating and will continue to do so for some time after the debris fire is out. Significant values of q_c occur only during the above period and then only within the lower portions of the concrete slab wherein the water vapor condenses.

At the zone between the hot portion of the concrete slab and the cooler regions which condensation occurs, steam will be generated provided the heat flow received from the hot region exceeds the rate of heat loss into the cool region. Under such a condition, the following heat balance exists at the interface wherein boiling occurs

$$K \frac{\partial T}{\partial x}\bigg|_{x=x_o-\delta} - K \frac{\partial T}{\partial x}\bigg|_{x=x_o+\delta} = \rho \cdot L \cdot p \cdot \frac{dx}{dt}\bigg|_{x=x_o} \qquad \text{(A-2)}$$

where

K = thermal conductivity of concrete,

L = latent heat of vaporization,

p = fraction, by weight, of free water in concrete, and

x_o = depth at which boiling occurs.

For situations in which no boiling occurs, the right hand side of Eq.(A-2)is zero. For the case of boiling, the depth x_o at which boiling occurs will increase as described by dx/dt.

A certain fraction of the generated steam will move downward into the concrete slab toward the shelter while the remainder will escape through the hot upper portion of the slab. The portion of the steam moving downward toward the shelter, which we will term $F(x_o)$, will increase with the depth x_o at which the steam is generated. The term q_c, which equals the rate of heat absorbed as a result of condensation of water vapor unit depth per unit crossection area of concrete can be expressed as

$$q_c(x,t) = h_w \cdot (T_s - T(x,t)), \tag{A-3}$$

where

x	=	depth at which condensation is being considered,
t	=	time,
h_w	=	heat transfer coefficient per unit depth and per unit crossection area,
T_s	=	temperature of steam, and
$T(x,t)$	=	temperature of concrete.

Here of course, the concrete at depth x must be cooler than the concrete at the depth x_o at which steam is being generated and must not exceed the depth x_1 at which the steam is depleted by condensation. If the flow of steam is sustained all the way into the shelter then x_1 equals the thickness of the concrete slab. On the other hand, if the steam is completely condensed within the concrete slab, then the minimum depth x_1 at which this occurs can be determined by solving the following equation for x_1

$$\int_{x_o}^{x_1} h_w \cdot (T_b - T(\xi,t))\, d\xi = \rho \cdot L \cdot p \left.\frac{dx}{dt}\right|_{x=x_o} F(x_o) \tag{A-4}$$

where the function $F(x_o)$ represents the fraction of the generated steam moving deeper into the slab and T_b represents the temperature of boiling water.

The critical depth x_1, of course, will increase as a function of time t.

The rate at which condensation occurs per unit depth per unit crossection area can be evaluated from the following equation

$$\frac{dW(x,t)}{dt} = \frac{q_c(x,t)}{L} \qquad \text{(A-5)}$$

where L refers to the latent heat required to condense a unit weight of vapor and W refers to its weight.

In addition to the heat flux $q_c(x,t)$ absorbed by the concrete due to condensation, part of the sensible heat of the condensate will also be transferred to the concrete. The rate at which the condensate heats the concrete q_c' can be expressed as

$$q_c'(x,t) = C_w \frac{dW(x,t)}{dt} (T_b - T(x,t)) \qquad \text{(A-6)}$$

where

ρ_w = density of water, and

C_w = specific heat of water.

The total heat flux to the concrete is equivalent to the sum of the heat exchange involved in condensing the vapor q_c and the transfer of sensible heat from the hot condensate to the concrete q_c'.

A.2 Boundary Conditions

A.2.1 Concrete-Debris Interface

The transfer of heat either from the hot burning debris into the upper surface of the concrete slab, or from the bottom surface of the slab into the shelter involves a number of extremely complex phenomena which require approximation. At the top surface, all modes of heat transfer are important in transferring heat from the burning debris to the concrete slab.

Much of the complication arises from the heterogeneous nature of debris, and the transient nature of both the fire and the debris temperatures. One can approximate the average heat flow over the surface by use of a mean heat transfer coefficient $h_d(t)$ associated with the average temperature $T_d(t)$ of the debris close to the concrete. The resultant heat flux into the concrete can be represented mathematically by

$$h_d(t)\cdot(T_d(t) - T(0,t) = - K \frac{\partial T}{\partial x}\Big|_{x=o} \tag{A-7}$$

Since the heat flux is determinable experimentally using $T(0,t)$, a knowledge of either $h_d(t)$ or $T_d(t)$ suffices to determine the other. The problem here is that the average temperature of the debris close to the concrete is highly variable and therefore difficult to measure because of the discrete nature of the debris. Nevertheless, some measure of the average temperature of the debris close to the slab is needed to establish the driving force for the heat transfer.

Since the heat transfer coefficient should not change drastically as a function of time, we will for the time being assume it is constant. For this condition Eq.(A-7) becomes

$$h_d\cdot(T_d(t) - T(0,t)) = - K \frac{\partial T}{\partial x}\Big|_{x=o} \tag{A-8}$$

A.2.2 <u>Shelter Ceiling</u>

The two major mechanisms by which heat is transferred into the shelter from the shelter ceiling aside from the possible entry of vapor, are radiation and convection. There are two aspects to the radiant transfer, namely:

- radiant exhange between the ceiling, walls and floor, and
- absorption of radiation by air.

Large concentrations of water vapor within the shelter will appreciably increase the absorption of radiation by air within the shelter space.

Convection is particularly difficult to describe because of the appreciable vertical statification of air temperature and because of the natural circulation of air.

Accurate descriptions of each of the above heat transfer mechanisms requires very complex analyses beyond the needs of this program. Also, the heat transfer problem will be appreciably altered by the presence of personnel within the shelter. A more tractable, although less accurate approach, is to consider the air sufficiently well mixed to be at a uniform temperature, and describe the heat transfer to the air as the product of a constant heat transfer coefficient h_a and the difference in temperature between the air T_a and the temperature T of the shelter ceiling. Mathematically, the rate of heat transfer into the air space q_a will be described by

$$q_a = h_a \cdot (T(D,t) - T_a) \qquad \text{(A-9)}$$

where

h_a = heat transfer coefficient between air and concrete, and

D = thickness of concrete slab.

Heat losses to the walls and floor q_w will be described by

$$q_w = h_a \cdot (T_a - T_w(0,t)), \qquad \text{(A-10)}$$

where the term T_w represents the average temperature of the wall and floor surfaces. Wall and floor temperatures $T_w(0,t)$ should be below the boiling point of water and may be calculated by applying the transient diffusion heat conduction noted by Eq.(A-1) with q_c equal to zero and considering the wall and floors as semi-infinite bodies. Equation (A-10) of course, describes the heating of the surface. The heating q_w will alter the temperature

gradient at the surface of the wall or floors as

$$h_c \cdot (T_a - T_w(0,t)) = -K \left. \frac{\partial T_w}{\partial x} \right|_{x=0} \quad \text{(A-11)}$$

Air temperature may be predicted by solving the following equation

$$\rho_a \cdot V_a \cdot C_a \cdot \frac{dT_a}{dt} = q_a - q_w \quad \text{(A-12)}$$

where

ρ_a = density of air,

V_a = volume of shelter space, and

C_a = specific heat of air.

APPENDIX B

DEBRIS SIMULATION, A PRELIMINARY ANALYSIS

APPENDIX B

DEBRIS SIMULATION, A PRELIMINARY ANALYSIS

At overpressures exceeding about 2 psi, buildings will commence to suffer significant blast damage from a nuclear burst and certain amounts of the building and its content will be swept out depending on the location and construction of the building. The amounts of debris will, of course, increase with overpressure and its duration.

At low pressures, only small amounts of debris will be produced that for the most part will be relatively large in size and involve appreciable fuel. This debris will consist mostly of building contents, drop ceiling panels and light interior partitions. Although it is likely to be piled preferentially, it generally will remain on the floor of origin so long as exterior walls remain in place (unless very large window openings exist). As overpressure increases, heavier interior partitions and exterior partitions will also fail. At overpressures just slightly above that required for exterior wall failure, most debris will be swept from framed structures. Thus the location of the debris (inside or outside the structure) is closely related to the wall strength.

At higher overpressures, the debris involves higher percentages of noncombustibles, travels greater distances and ends up broken into smaller pieces. Distances at which the debris is deposted will also depend on the elevation angle associated with the direction of the blast wave and the duration of the blast. Further increases in overpressure will result in more uniform distributions of debris due to greater dispersion over several building separations.

Realistic reproduction of the quantity, sizes, and distribution of the debris are important in simulating debris fires and must, of course, be adhered to as close as knowledge permits

in order to obtain an accurate appraisal of the possible consequences of debris fires on shelters and the hazards of shelterees.

One can envision the two types of debris configurations as having particular consequences on the environment within a shelter. The first is direct heating by debris which is confined to the buildings -- either as a consequence of low overpressure, strong walls, or possibly due to an overhead nuclear burst. The effect of fires in such debris on the shelter environment has been treated in fire tests 70-1 through 71-4. The second type of debris configuration in which substantial quantities of the debris are cast out of the shelter buildings and/or surrounding buildings and are strewn about the ground sufficiently close to the shelter building affects the quality of air drawn into the shelter. This debris condition will be elaborated on in the remainder of this appendix.

In choosing realistic debris conditions for the experiments, several points must be considered, namely:

- the attack conditions should be chosen such that there is an appreciable probability that substantial quantities of debris are deposited in the vicinity of air intakes located on one or more sides of a building,
- the debris should be representative of that produced by many bursts,
- the type of built-up area chosen should lend itself to reasonably accurate predictions of debris on the basis of existing knowledge,
- the built-up area should conform to areas containing appreciable numbers of shelters, and
- the resultant debris should present those cases where a significant fire threat to shelter personnel is suspected.

On the basis of these constraints, we will appraise the effects of a nuclear attack on shelters within high-rise residential type areas. While we will be specifically looking at the consequences of a blast of 9.5 psi overpressure from a

nuclear attack, the debris results also apply to a number of other attack conditions of somewhat higher overpressures from lower yield bursts. Here we shall choose 12-story steel or reinforced concrete frame buildings having base dimensions of 100 by 100 ft with masonry panel walls. The building density shall be 7 percent in conformity with values found by SSI in their study of existing shelter locations. The specific type of area is classified by SSI as number 1 and contains approximately 24 percent of the 691 shelters within the areas surveyed.

For purposes of this preliminary analysis, Fig. 12 of the URS Final Report by Edmunds (Rev. 3) was used which indicates that practically all the walls and content will be swept out of such buildings at 9.5 spi and deposited over the ground. Figure 4.5 of IITRI Final Report by Feinstein (Ref. 4) was used to describe the size of the building fr ents formed (see Table B-1). Although current studies (Refs. 5 and 6) would indicate that these fragments are smaller than those initially formed during wall failure, they may be fairly representative of the final debris after transport which will include collisions with other parts of the structure and with the ground.

Table B-1

ASSUMED FRAGMENTATION OF NONCOMBUSTIBLE BUILDING DEBRIS

Equivalent Radius of Debris, in.	Percent of Debris
0 to 2.32	4
2. to 4.64	13
4.64 to 6.96	32
6.96 to 9.28	5
9.28 to 11.60	46

Use of the calculated particle trajectories of the various debris fragments shown in Figs. D-4.11 and D-4.12 of the IITRI Final Report by Ahlers (Ref. 7) indicates that each of the particle sizes from the masonry panels will be distributed over the ground in a manner that will vary to within $\pm$ 30 percent on a lbs/ft^2 basis. This is largely a result of the large transport to separation distances between buildings such that each of the various sizes of debris is spread over areas encompassing several buildings. Ground in the vicinity of unexposed walls will be shielded from such debris and may or may not be covered with substantial debris originating from the affected buildings. Except for such areas, it will be assumed that all the ground in the particular area is uniformly covered with the same quantities and sizes of debris. Furthermore, we shall assume that all of the brittle debris is broken up into pieces similar in size as that noted in Table B-1 for masonry panel walls. Remaining debris will be assumed to be broken into somewhat coarser pieces according to its strength.

Figure 12 of Ref. 3, indicates that the 9.5 psi overpressure will convert 68 percent of the buildings material to debris which will be swept out of the building along with the content of the building.

On the basis of a building density of 0.07, each of the 100 by 100 ft buildings shall be located on an average land area of

$$\frac{100^2}{0.07} = 142,857 \text{ ft}^2 \qquad \text{(B-1)}$$

According to Table 1 of Ref. 3, the volume of material in such buildings is equal to 0.1 of the enclosed volume of the building and is 92 percent incombustible. From the same reference, typical contents of residential buildings consist of 3.5 lbs/ft^2 of combustible material and 1.5 lbs/ft^2 of incombustible material.

If we use an average density of 80 lbs/ft^3 for the incombustible material and 35 lbs/ft^3 for the combustibles, then the total weights of combustible C_m and incombustible debris I_m per building shall be

$$I_m = 0.92 \times 80 \times 0.68 \times 0.1 \times 12 \times 10 \times 100^2 + 12 \times 100^2 \times 1.5 = 6.19 \times 10^6 \text{ lbs} \qquad \text{(B-2)}$$

$$C_m = 0.08 \times 35 \times 0.68 \times 0.1 \times 12 \times 10 \times 100^2 + 12 \times 100^2 \times 3.5 = 6.48 \times 10^5 \text{ lbs} \qquad \text{(B-3)}$$

For the case of uniform distribution over the ground, the debris will consist of 43.3 lbs/ft^2 of incombustibles and 4.5 lbs/ft^2 of combustibles for a ratio of close to 10 to 1.

The above analysis was used to provide preliminary data for selecting debris compositions and depositions for the fire laboratory shelter experimentation. It is expected to refine and expand the analysis to a broader range of conditions in the future to define a useful range of conditions for study.

APPENDIX C

EXPERIMENTS USING "DEBRIS CRIBS" PLACED ON A METAL PLATE

APPENDIX C

EXPERIMENTS USING "DEBRIS CRIBS" PLACED ON A METAL PLATE

There are three major uncertainties in predicting the thermal effects of debris fires on the transfer of heat into the shelter space. These are discussed below:

- The first is the mechanism of heat transfer from the burning debris to the upper surface of the concrete slab over the shelter space. In the analysis discussed in the second quarterly report, it was assumed that the rate of heat transfer to the surface of the slab was linearly dependent on the difference between the debris temperature $T_d(t)$ and surface temperature of the slab $T_u(t)$ as follows:

$$h_d \left[T_d(t) - T_u(t) \right], \tag{C-1}$$

where h_d represents the heat transfer coefficient.

- The second uncertainty is a knowledge of the average temperature of the burning debris as a function of time and how the debris temperature varies with the configuration and constituents of the debris pile.

- The third uncertainty is the effect of water application or more specifically a quantitative appreciation of:
  - the cooling effect of water on both the slab and debris as a result of contact with water, and
  - the cooling effect of the escaping water vapor on the debris.

In the previous analysis, only the cooling of the slab was considered since the effects of water on the debris were not known.

Procurement of the above information from debris fires over the shelter is most difficult because the concrete slab is a poor calorimeter and because of the large variations in the heating across its surface caused by the very heterogeneous nature of the debris. To circumvent these difficulties, a

number of debris fire tests were conducted using a 1-in.-thick, 24-in.-wide and 60-in.-long aluminum plate to monitor the heat fluxes from burning and to ascertain the effects of water application. The aluminum plate was split into two sections to allow water application to half of the plate while the other half remained dry. Debris consisted of wood and lath.

The first debris pile is illustrated in Fig. C-1 and conforms with typical mixtures of combustible and incombustible materials while the second debris pile is illustrated in Fig. C-2 and involves much less incombustible material to better appreciate the effects of varying the constituents of the debris. After several preliminary trials, one test was conducted using setup 2 without water while two tests were conducted using setup 1 with water. In each of the latter tests, water was applied near the time of peak debris temperatures. Both the quantity of water and period of application were varied. Results of these experiments are shown in Figs. C-3 through C-5. Temperatures affected by applying water onto the aluminum plate are illustrated by dashed curves while temperatures obtained without water are presented by solid curves. In each test in which water was applied, only half of the split aluminum plate was wetted while the other half remained dry.

C.1 Effects of Composition of Debris

Figure C-3 illustrates the temperature histories obtained with the debris setup 2 which consists largely of wood while Figs. C-4 and C-5 presents temperature obtained with setup 1 which differs only on having greater quantities of rock lath. Comparison of the solid curves of Fig. C-3 with those of Figs. C-4 and C-5 indicates that the added lath has an important effect in that it:

- delays the fire development,
- appreciably lowers the peak temperature of the debris, and
- appreciably extends the duration of the heating.

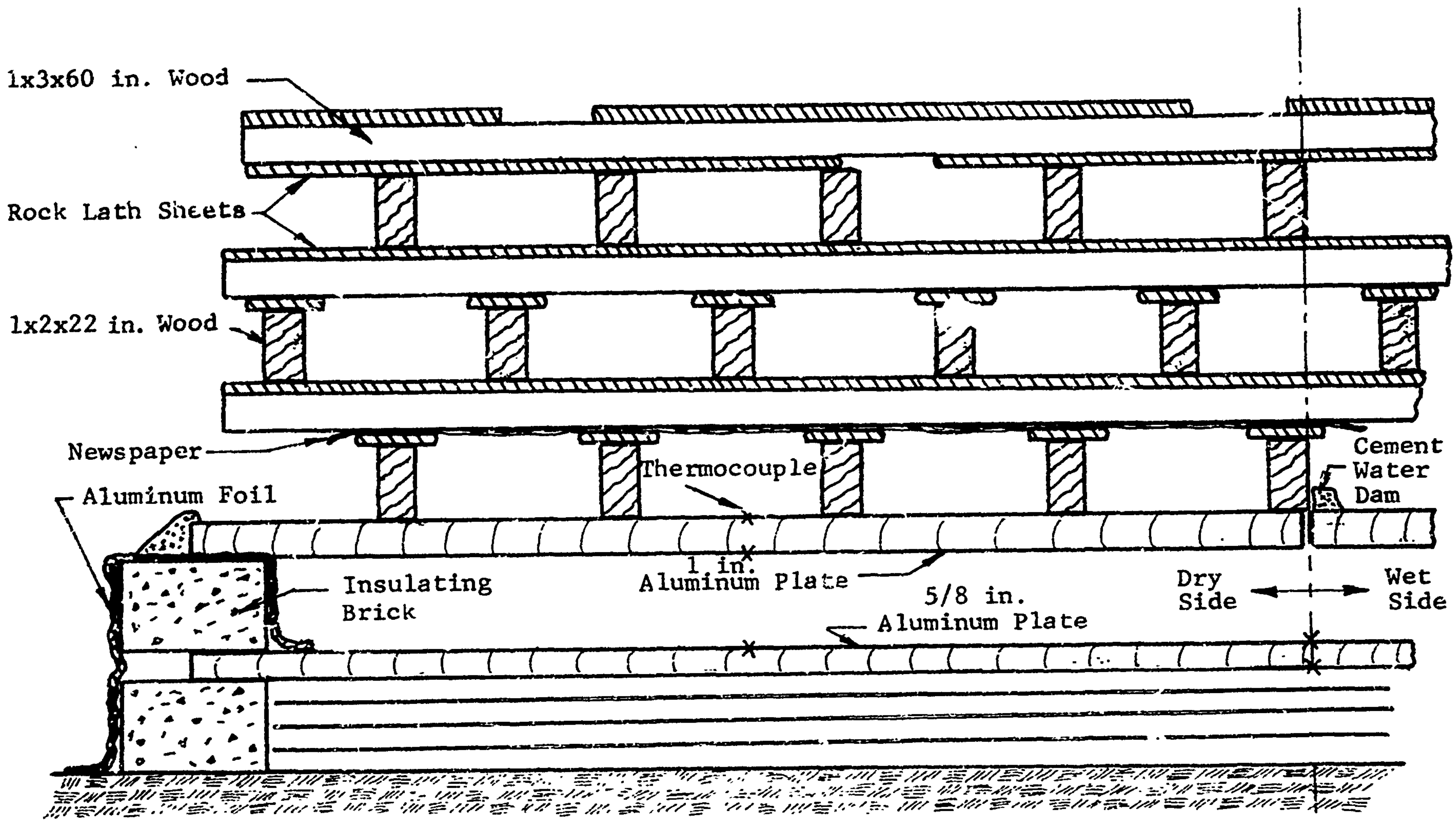


Fig. C-1 DEBRIS SETUP 1

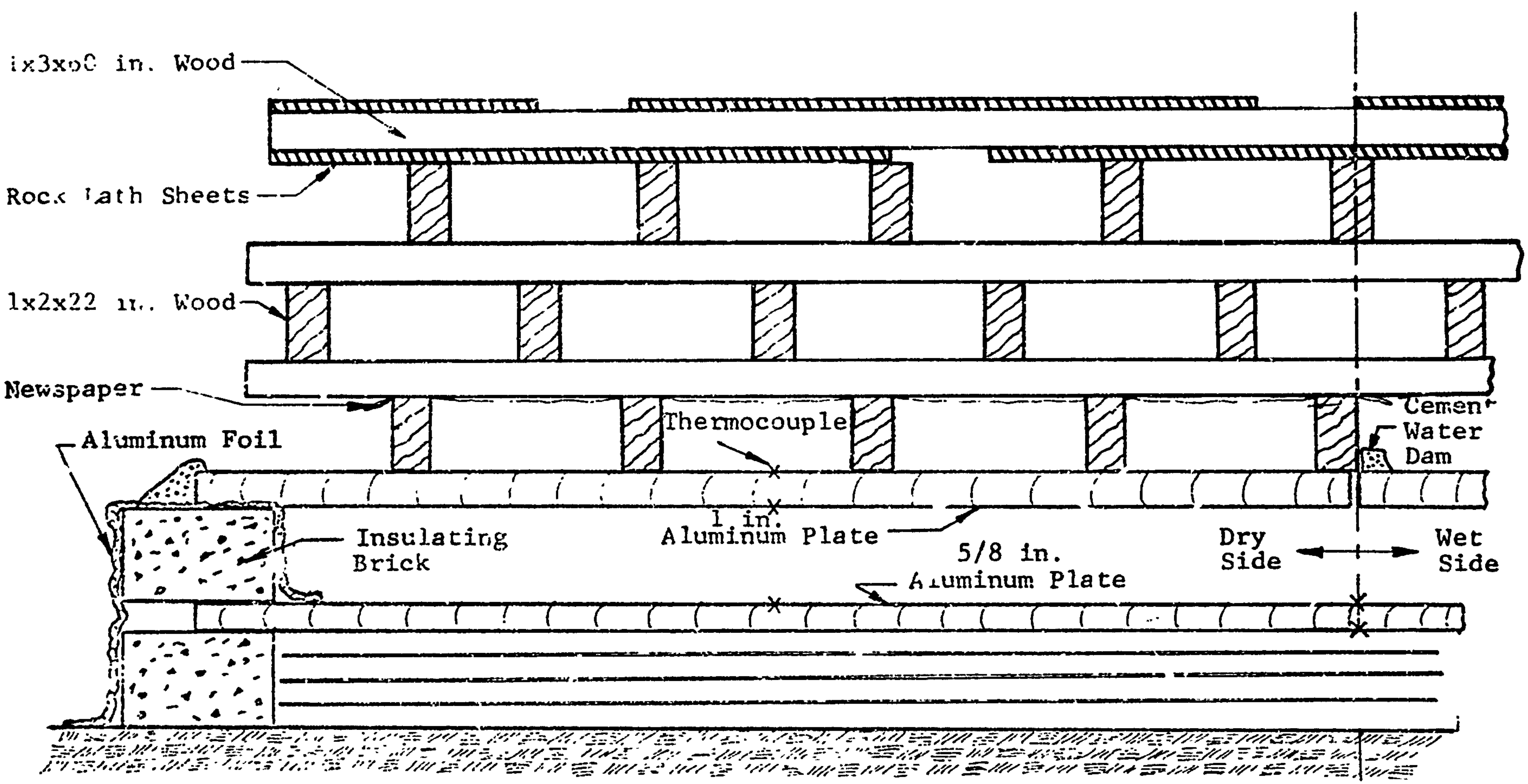


Fig. C-2 DEBRIS SETUP 2

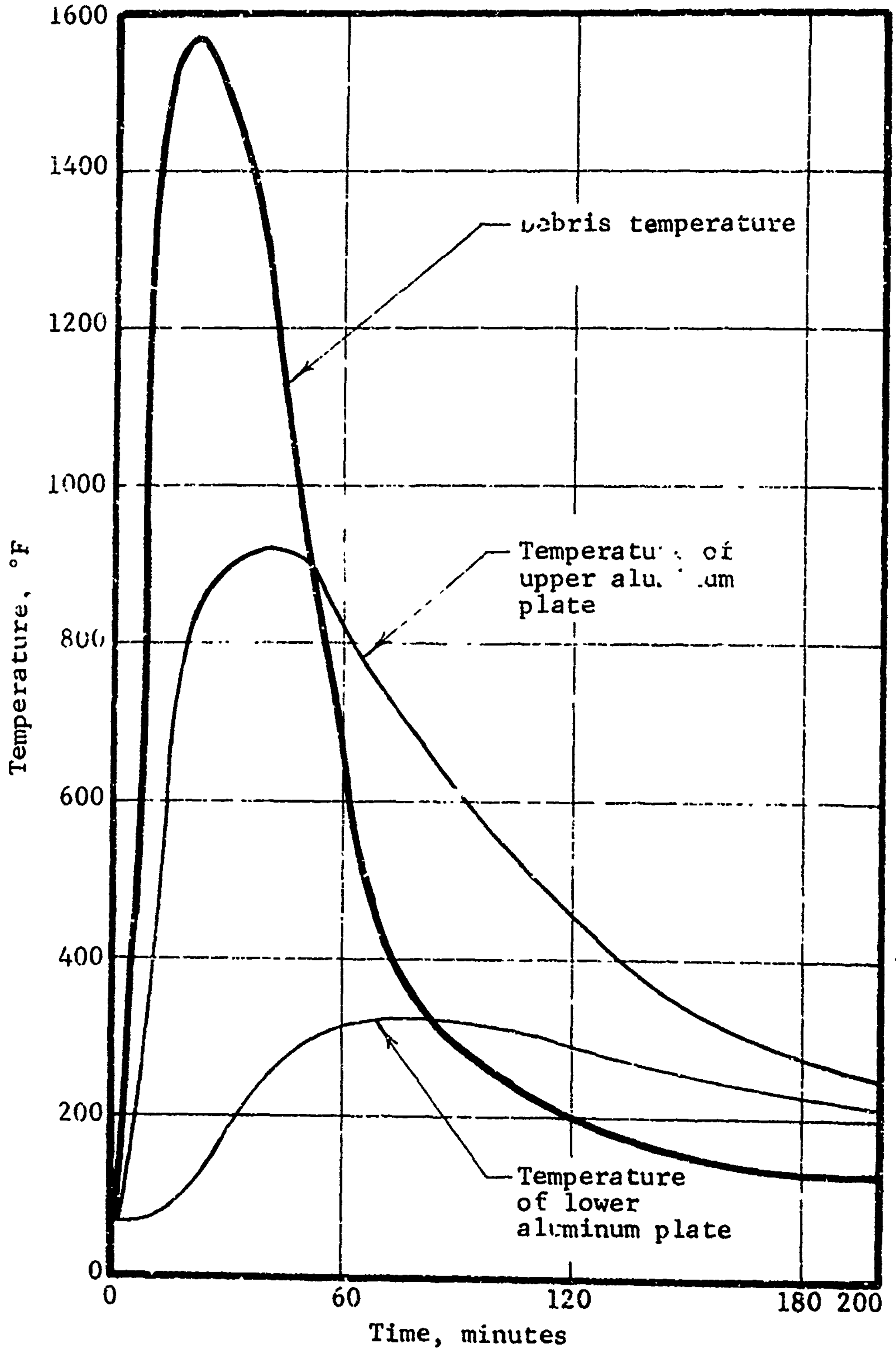


Fig. C-3 TEMPERATURES PRODUCED BY FIRE IN DEBRIS SETUP 2

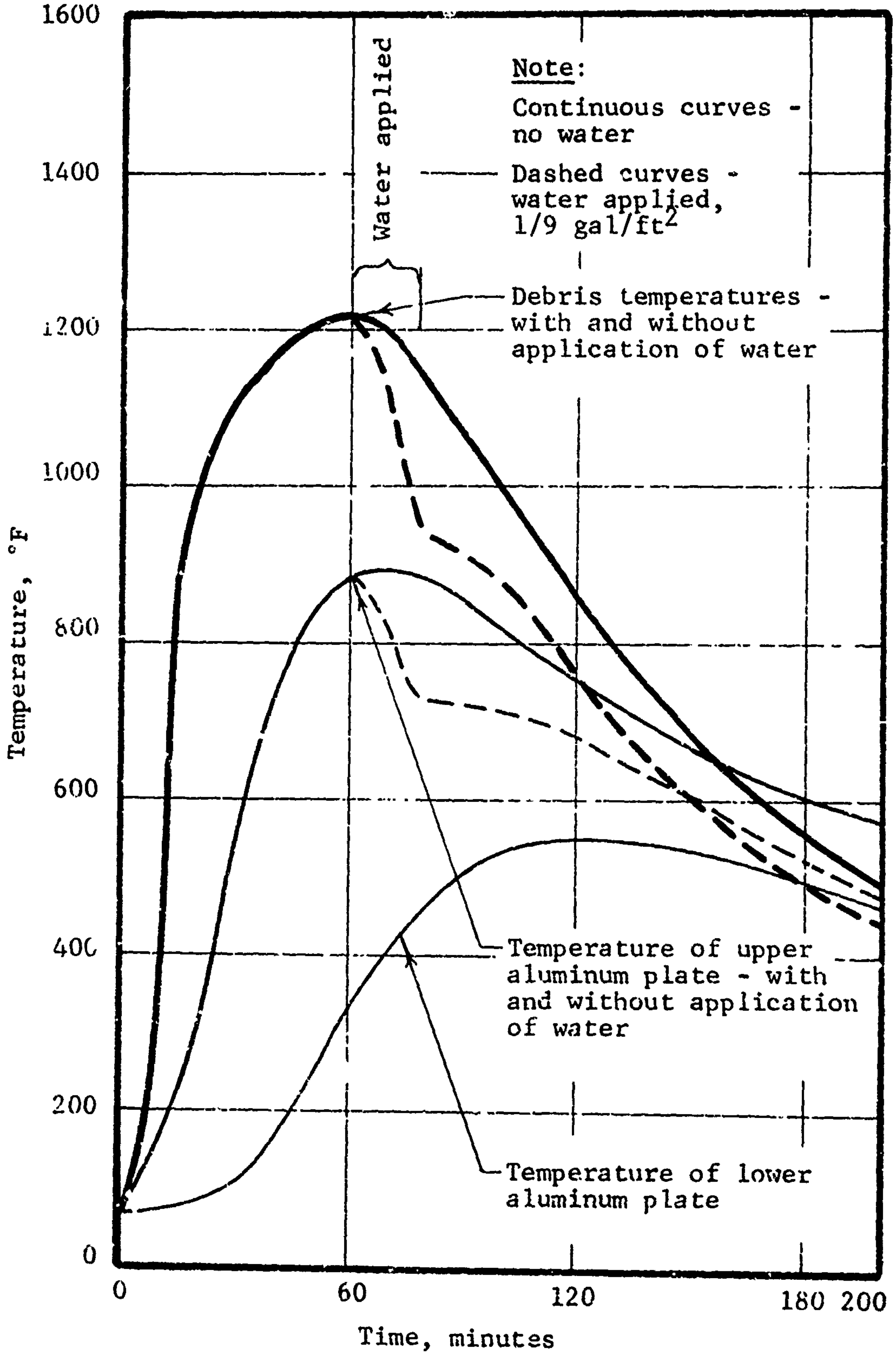


Fig. C-4 EFFECTS OF SMALL APPLICATIONS OF WATER ON TEMPERATURES OF DEBRIS SETUP 1

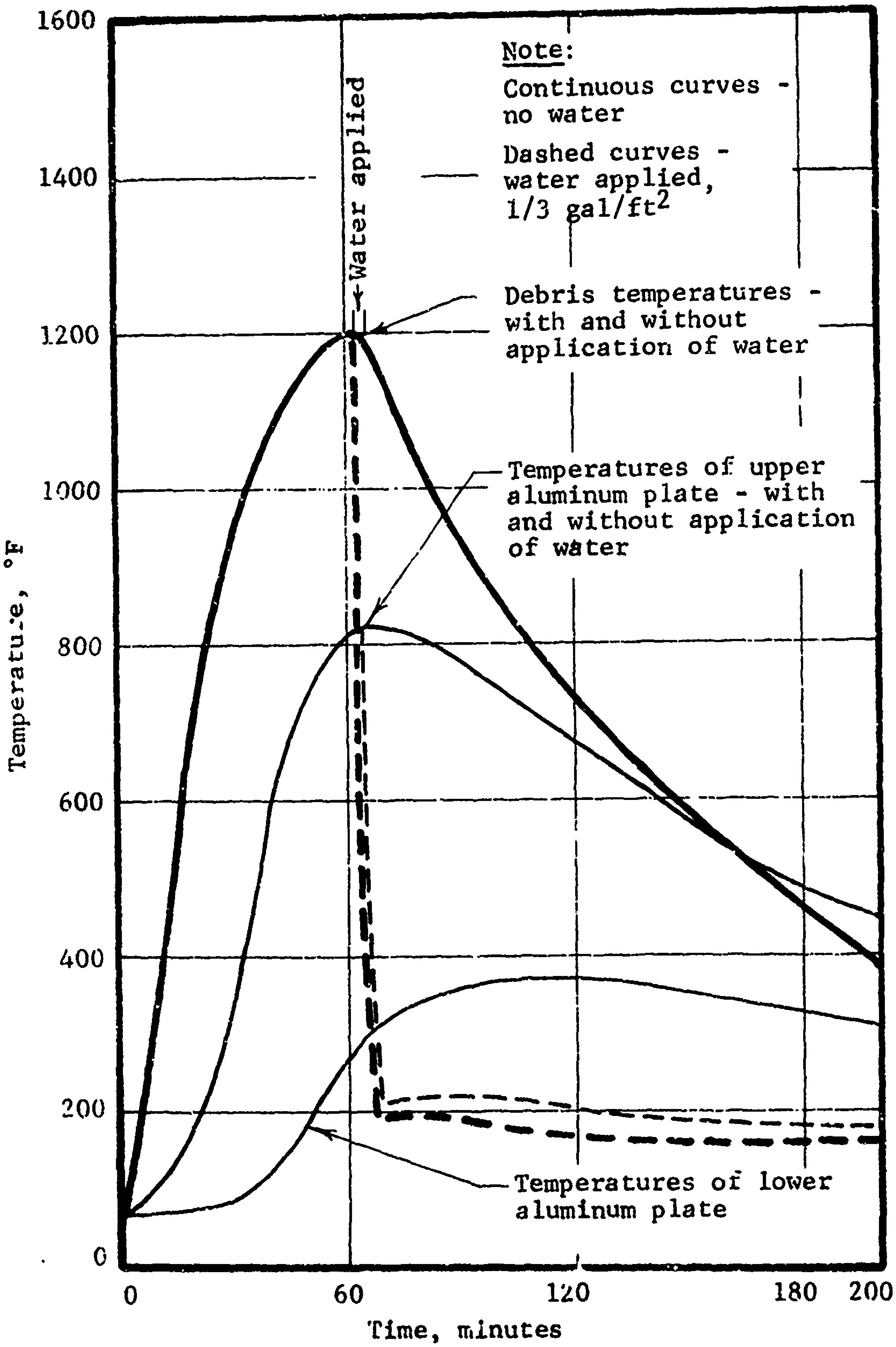


Fig. C-5 EFFECTS OF LARGE APPLICATIONS OF WATER ON TEMPERATURES OF DEBRIS SETUP 1

Therefore, larger amounts of incombustibles moderate the heating and extend the heating over longer times. Over sufficiently long exposure times, the total heating of the shelter space should be greater with the greater amounts of incombustibles. Whether or not this will aggravate the threat to shelter inhabitants depends on the thickness of the shelter slab and when cool outside air can be drawn into the shelter space. Since incombustibles delay fire development, early availability of cool outside air or debris removal would be most effective with debris fires containing large amounts of incombustibles.

C.2 Heat Transfer Coefficient -- Debris to Slab

Data presented in Figs. C-3 through C-5 allow one to use Eq.(C-1) to evaluate the heat transfer coefficient, h_d, in terms of the difference between the debris temperature $T_d(t)$ and the temperature of the upper aluminum plate $T_u(t)$ as a function of time using the heat flux determined from the rates of temperature rise of the upper and lower plates. Here one can use a variety of temperatures to check the assumption that the flux is linearly dependent on the temperature difference $T_d(t)-T_u(t)$. In order to accomplish this end a total of 13 evaluations of h_d were made using debris temperatures ranging from 780 to 1740°F. The resultant heat transfer coefficient h_d was found to range from 5.3 to 12.7 B/ft^2-hr-°F with an average value of 7.8 B/ft^2-hr. Part of this variation can be ascribed to the dependence of h_d on the debris temperature --- for example, the average value of h_d for debris temperatures of 1510 to 1740°F was 11.4 B/ft^2-hr-°F while the average value of h_d for debris temperatures of 780 to 1070°F was 7.3 B/ft^2-hr-°F. These values contrast quite well with the value of 10 B/ft^2-hr-°F used in earlier calculations and suggest that the assumption of linear dependence is reasonable. Predictions could, however, be improved by allowing the coefficient to vary with the debris temperature.

C. Effect of Applying Water

Figures C-4 and C-5 also illustrate the cooling effect of applying water to the upper aluminum plate on the temperatures of the debris and aluminum plate. Different quantities of water were applied over different periods to better appreciate how water should be applied most effectively. Comparison of the dashed curves with the solid curves indicates that the cooling effect of water is great -- both in reducing the temperature of the debris and the aluminum plate. Also it may be observed that the cooling is roughly proportional to the total quantity of water used and is not highly dependent on the duration over which the water is applied.

Also the data indicate that 60 percent of the water is evaporated by the upper aluminum plate while the remaining water is expended in cooling the debris. This is in variance with the assumption used in the previous analysis in which all the water was assumed to cool the slab by evaporation leaving the debris unaffected. This result points up the importance of the heat capacity of the debris at the time of water application and suggests that the application of water is most effective with shallow, low heat capacity debris piles.

The above described experiments have offered increased insight into the mechanism governing heat transfer to the shelter ceiling slab. However, they suffer the weakness that the aluminum plate does not respond to water application in the same manner as concrete. For this reason and to further examine moisture migration within the slab, additional small scale tests are being contemplated using a debris crib fire over a several inch thick concrete slab.

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SUMMARY

FIRE LABORATORY TESTS - PHASE II
INTERACTION OF FIRE AND SIMULATED BLAST DEBRIS

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FIRE LABORATORY TESTS - PHASE II
INTERACTION OF FIRE AND SIMULATED BLAST DEBRIS

1. INTRODUCTION

Fire and its effects on shelter occupants, caused either by explosion of a nuclear weapon or by subsequent events, has been of concern to the Office of Civil Defense (OCD) for many years. The nature of the research efforts has varied in keeping with the continuing evolution of OCD shelter philosophy. The present study encompasses analytical and experimental investigations leading to the development of information to provide a sound technical base from which to design occupant fire protection into basement shelters in new construction. Specific goals are to:

(1) Evaluate the flow of smoke, toxic gases and heat into basement shelters from various types of fire load in the building above the shelter.

(2) Develop recommendations on permissible fire load in the building above a basement shelter.

(3) Develop recommendations on the location and capacity of ventilation intakes for basement shelters with the objective of obtaining the least expensive air intake consistent with 85 to 95 percent survival of shelterees.

(4) Develop recommendations for fire control methods to be used with blast slanted basement shelters and assuming considerable blast damage to the building above the shelter.

(5) Conduct and evaluate experiments to determine ventilation problems in basement shelter associated with fire loads on first and second floors and debris fires extending well beyond the bounds of the structure.

(6) On the basis of preliminary tests previously conducted, perform experiments to evaluate the effect of water countermeasures.

(7) Evaluate the effect of other expedient type countermeasures (e.g., removal or scattering of debris during and/or after start of fire).

(8) Evaluate effect of operating emergency ventilating equipment during fire period.

These goals reflect the concept of slanting new construction (i.e., incorporating modifications during the design stage) to provide shelters with enhanced resistance to the combined effects of nuclear weapons; blast, fire and fallout. There is little question that below grade shelters of concrete construction designed to withstand 10 psi or more overpressure, can also maintain structural integrity under all imaginable fire exposures. Questions to be answered are to provide life safety for the shelter occupants from penetration of heat and fire gases into the shelter space. These include both fire environments; as determined by fire load and level of blast damage and as modified by various conceptual countermeasure activities.

The studies reported herein center around large-scale fire experiments. These are being conducted in a reusable two-story fire test facility which provides a 60-man (600 ft^2) basement shelter, fully instrumented for assessment of the flow of heat and fire gases. By providing for full-scale experiments under laboratory conditions, the facility is adaptable to a systematic study of effects of variable parameters, as well as to spot check applicability of designs based on theoretical or small-scale laboratory studies.

Included in the first year of effort were construction and general instrumentation of the large-scale fire test facility and conduction of preliminary tests. Reference 1* provides a detailed report of this portion of the program. During the current reporting period (July 1970-December 1971) further instrumentation has been added and experiments have been

*Waterman, T. E., Fire Laboratory Tests - Phase I, OCD Work Unit 1135A, Contract DAHC 20-70-C-0206, IITRI Project J6183, September 1970.

conducted for debris piles within and beyond the bounds of the structure above the shelter. These have been augmented by development of an analytical model of heat flow through the shelter ceiling slab and by conduct of several small-scale debris tests on an aluminum plate. Their purpose is to aid in assessing the potential benefit of debris removal and water application as countermeasure techniques and to aid in predicting the heating effects of other debris piles or thicknesses of ceiling slab are considered. Several large-scale countermeasure benefits have also been examined.

2. THE FIRE TEST FACILITY

The large-scale fire experiments are being conducted in the test facility constructed under Contract DAHC 20-70-C-0206 (Ref. 1). This facility consists of a 20 by 30 ft basement shelter space topped by a two-story reinforced concrete rigid frame upper shell. The shelter ceiling is a 12-in.-thick reinforced concrete slab. Two outside shelter entrances, a ramp and a stairwell provide locations for assessing entryway debris pileup as well as for evaluating ventilation intakes. Photographs of the structure are shown as Fig. 1, and a plan view is included as Fig. 2. As presently constructed, the facility has the fire zones approximately 50 percent enclosed. This can be readily increased by the addition of temporary panels to the remaining openings. As shown by Fig. 2, portions of the shelter ceiling (first story floor) and the second story floor can be removed to vary the fire zone configuration and its access to the shelter space. In addition, changes in shelter ceiling thickness or composition can be studied at these locations. For further construction detail, the reader is referred to Ref. 1.

Ramp Entrance

Overall View of Structure

Stairwell Entrance (Behind Right Rear Wall in Overall View)

Fig. S-1 FIRE TEST STRUCTURE AND SHELTER ENTRANCES

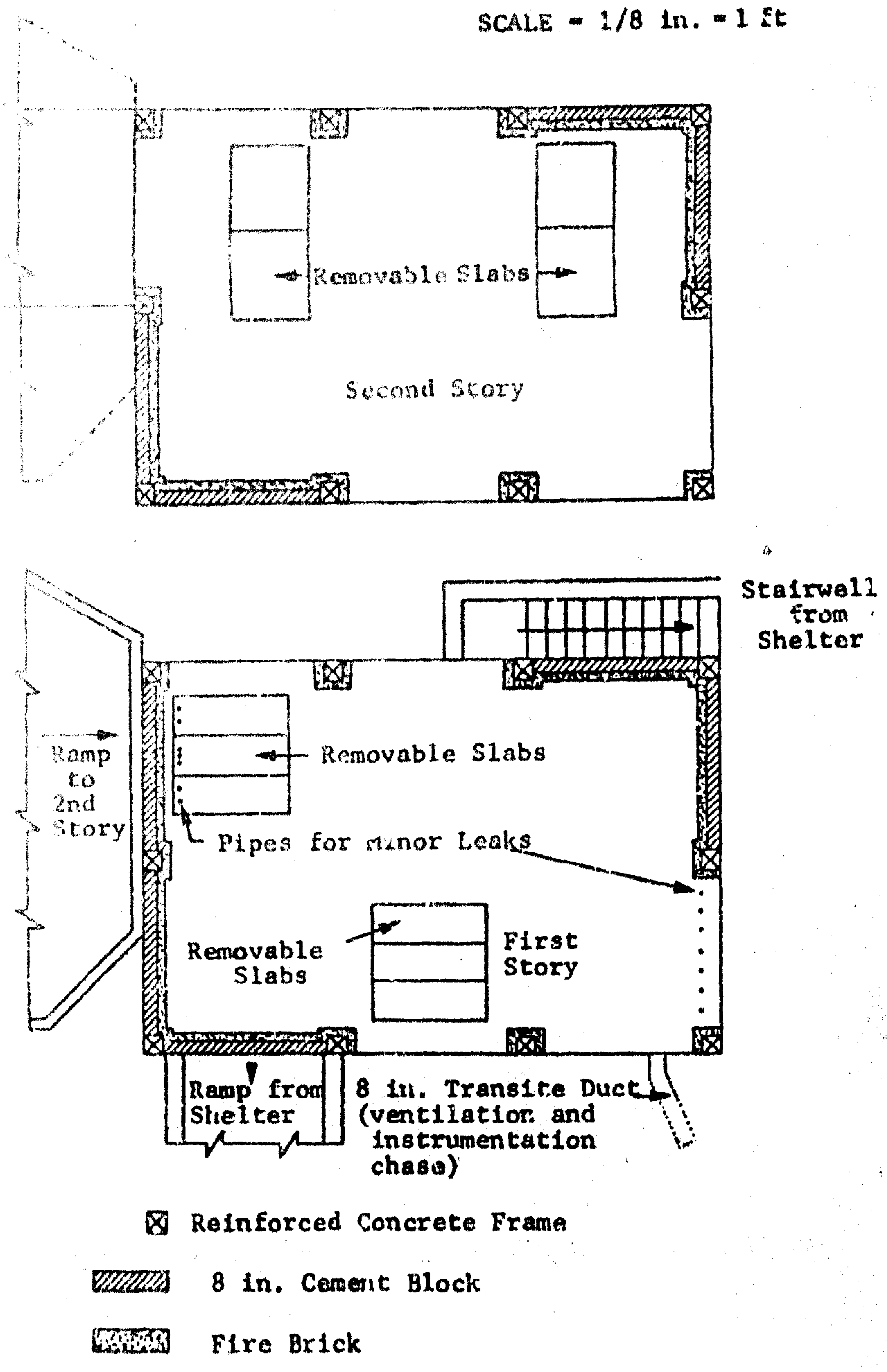

Fig. S-2 PLAN VIEWS OF FIRE TEST FACILITY SHOWING GENERAL CONSTRUCTION FEATURES

3. SUMMARY AND CONCLUSIONS

Here we shall summarize what is known about debris fires as well as countermeasures to reduce the effects of excessive heat or toxic gases on shelter occupants. Included is a specification of areas of major ignorance that require resolution to identify optimally effective means for coping with such fires. While major inroads have been and, hopefully, will continue to be made into such areas, it is clear that a number of needs will remain to be resolved at the culmination of the present program.

3.1 Heat Loading

3.1.1 Debris Piles

Generally speaking, fires within residential type debris piles will, within the first hour, deliver their maximum heat flux into a shelter of a few thousand Btu per square foot and rapidly subside thereafter. Peak heating of the shelter interior will occur several hours later. For situations involving relatively cool environmental air temperatures, the heat flow into the concrete will reverse direction after several hours and transfer substantial quantities of heat from the concrete slab to the external environment. A total of a few thousand Btu will be absorbed by each square foot of heated surface during the several hours following fire start. This sequence of events is appropriate to other occupancies although with modified time scales.

Experiments have shown that heat loading of an unventilated shelter through a 12 in. ceiling slab by a residential debris fire equals that of the expected occupants. For a 5 in. slab, the heating reaches an equivalent of four added occupants per shelter space. Where less blast damage or less blanketing types of noncombustibles permit freer burning, heat loading of the shelter is reduced. Higher fuel loadings produce increased but not proportional heat loads on the shelter. A library

loading with heavy masonry partitioning produced the equivalent heating of 2-1/2 occupants per space through a 12 in. slab and 7 occupants per space through a 5 in. slab.

At present there are two recognized areas of ignorance for projecting the measured results to other situations. The first is a poor quantitative understanding of the mechanisms dominating the transfer of heat from burning debris to the concrete, and the second is a poor quantitative understanding of how this heat flow is affected by the application of water onto the heated concrete. Detailed mechanistic descriptions, while most satisfactory, are impractical at the present time. A more attainable goal utilizes empirical means that describe the heat flow in terms of temperature difference between the debris and concrete.

3.1.2 Slab Thickness

The thickness of the concrete slab is of key importance in affecting not only the magnitude of the heat flux into the shelter space but also the times at which the peak fluxes occur. Thin slabs result in increased heat transfer through the slab by conduction and by the vaporization and condensation of free water, produce more severe heating of the shelter and cause it at earlier times when ventilation air may be restricted. The result, of course, will be a more rapid and pronounced increase of the heat load within the shelter that will be especially serious if appreciable quantities of steam penetrate the thin slab. Accurate predictions of the effect of slab thickness will be possible once the present computerized analysis is completely checked out. Otherwise, there are no significant obstacles involved in making such predictions.

3.1.3 Water Vapor

As noted earlier, the importance of the generation and movement of water vapor within concrete has important effects on the transfer of heat into the shelter space. Because of the limited range of temperatures experienced by the concrete on

exposure to debris fires, practically all of the evolved water will be free water. Since the amount of free water in concrete will vary with the humidity, conditions of high humidity are conducive to increased heating of the shelter space.

At the present time, the internal generation of water vapor is being described as a boiling process that occurs at increasing depths within the concrete. Practically all of the evolved vapor is released within the first hour for the 1-ft-thick concrete slab of test 70-2 and involves free water within the first few inches of concrete. Part of this water vapor escapes through the heated surface of the concrete; part is condensed out at deeper and cooler depths within the concrete; and part will enter the shelter in cases of thin slabs and/or intense, long duration debris fires.

Hopefully, more data will be forthcoming from future tests with the slabs instrumented to check the present description used to predict the effects of water vapor. Most information will come from collection of water vapor that passes through the 5 in. slab and comparison of its weight with that predicted by the present analysis. Limited experimentation with a slightly thinner slab is also being considered.

3.1.4 Initial Temperature

Even though no studies have been undertaken to appreciate the effect of the initial temperature, one can at least to the first order approximation consider that any reasonable temperature variation either up or down will be additive on the shelter temperatures. Temperature variations are not expected to be large especially since building temperatures are usually held within narrow ranges.

3.2 Countermeasures Applied to Shelter Ceiling Slab

A variety of countermeasures may be used to diminish the consequences of debris fires on the shelter ceiling. Here we

will limit discussion to postattack actions such as the removal of hot and burning debris and the application of water. Experimental evidence indicates that application of an average of 1/3 gal of water per ft^2 of heated surface at about 1/2 hour following the start of a residential debris fire will reduce the peak heat flux into the shelter to values about one-fourth that without water. Similar reductions of temperature rises and heat fluxes to the shelter are predicted by analytical means if the debris is removed 1/2 hour after ignition.

Predictions of the effect of debris removal present no difficulties presuming a knowledge of the subsequent environmental air temperatures. Heated environmental air, of course, could have serious consequences on shelter inhabitants if it is sustained for many hours.

At present, predictions of the effect of water application suffer from a lack of knowledge of the quantitative effects of water in altering heat flow to the concrete slab due to cooling and extinguishing of hot burning debris immediately above the heated surface of the concrete slab. These answers will be pursued in future experimentation.

3.3 Toxic Gases

Experiments with contained debris (70-1 through 70-6) indicate that localized debris fires of moderate depth do not generate toxic gases for long periods. The debris was representative of that created by the destruction and mixing of interior partitioning and building contents. This type of debris burned with sufficient intensity that the gases generated rose quite quickly and should not obviate a shelter by gas accumulation at ventilation points.

When the debris (interior partitions and contents) extend beyond the structure and surround shelter vents, a period of time exists when the vent cannot be used. Multiple vent locations can often solve this problem or button-up can be considered

since this period usually will occur prior to significant heat loading of the shelter ceiling. Localized clearing of the ventilation intake provides significant benefit (71-5,6) so long as the general air quality of the entire area has not been obviated.

Debris piles of increased depth with a composition representative of destruction of total structures and contents can produce slow burning fires whose gases show a tendency to hang along the ground. Whether or not a large number of such fires over large areas of high building density would cause general blanketing of an area remains to be resolved. Fortunately, recent advancements in the state of the art for the analysis of stratified flow permit combined analytical and experimental assessment of the problem and such study should be initiated. Solution of this problem would define those specific portions of the total urban area where more complex countermeasures might be required as part of effective slanting. In conjunction with this will be the need for means to more rapidly assess actual debris patterns for specific building complexes and attack conditions. This technology exists but needs implementation in the form of a computer code.

Debris directly over the shelter space can cause a toxic gas problem during shelter button-up if wind induced pressures are such that gases are driven directly from the pile down through cracks in the shelter envelope. Where these are minor, shelter pressurization and/or crack sealing can solve the problem. More significantly the phenomenon points to the importance of examining each structure for slanting so that no major flaws are permitted in the continuity of the shelter envelope (unprotected stairwells, shafts, pipe chases).